Renewable and Sustainable Energy Reviews 15 (2011) 2095–2122

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

The role of the thermally activated desiccant cooling technologies in the issue of energy and environment

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A R T I C L E   I N F O

Article history:
Received 11 August 2010
Accepted 24 January 2011

Keywords:
Energy resources
Environmental condition
Thermal comfort
Desiccant cooling

A B S T R A C T

This paper presents the review of the development and application of the thermally activated desiccant cooling technologies. The paper first introduces the global problem of energy and the environment related to the consumption of the carbon-based energy sources (gas, oil and coal). The contribution of the building sector to the above problem so as to maintain indoor environment providing human thermal comfort is shown. In this paper, the alternative methods for the provision of the human thermal comfort through thermally activated desiccant cooling technologies are discussed—solid desiccant, liquid desiccant and hybrid desiccant cooling systems. These technologies are potential alternatives to the mechanical vapor compression cooling technologies in the provision of human thermal comfort conditions. However, the development and application is mostly in developed and advanced developing countries. For a global scale solution to the problem of energy and environment contributed by the building sector for maintenance of comfortable conditions, dissemination of ideas and technologies to the developing world (Africa, South and South East Asia, South America) enhances the applicability and practicability of these technologies.

Contents

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1364-0321/$ – see front matter
doi:10.1016/j.rser.2011.01.013

1. Introduction

The global environmental problem is a serious one. The depleting conventional energy resources are other major issues. The world population is increasing every year. The human demand for better and comfortable condition is getting high. Urbanization is happening around the world. Industrialization is taking place in every corner of the planet. The above problems are complex as there are many parameters and considerations to be deeply looked into. These situations have become globally political, economical, and technological issues. Hand in hand solutions for these problems are a must to attain a common goal. Hence these issues of energy, environment, and technology are interrelated to each other and must be treated with interconnectivity if we have to attain clean and greener environmental conditions for humanity's survival (see Fig. 1 for the diagram) [1].

According to Lund [2], technological innovation is needed for future sustainable energy systems. From this, greenhouse gases emission such as carbon dioxide can be maintained, or if not, reduced. This will involve both political and technological will in tackling the issue through energy conservation, carbon sequestration and capture. In addition, development of carbon-free energy resources should also be given priorities as gradual alternative to carbon-based energy sources. Example, French cut the carbon dioxide emission by 27% in less than 10 years despite increasing energy consumption [3].

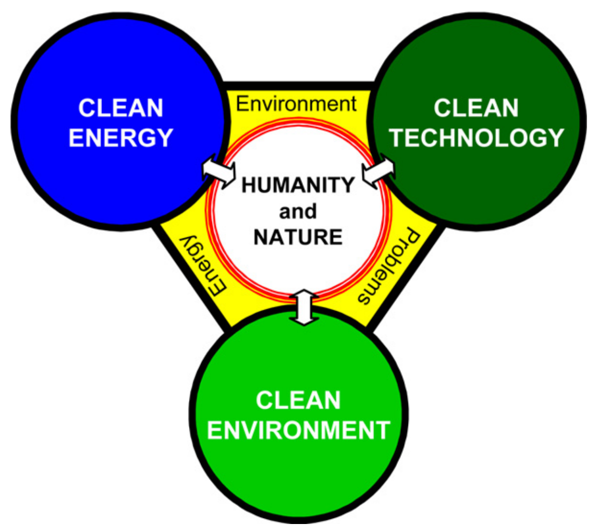

Fig. 1. Interrelated concept of the issues of energy, environment and technologies to the survival of humanity and nature [1].

2. Energy and environmental issues

The problem of energy consumption is related to environmental problems. Burning of conventional energy sources emits lot of greenhouse gases (GHG) particularly CO_2 [4]. The CO_2 emission is increasing every year which mostly comes from the developing region [5]. The increasing CO_2 emission from the developing world is due to the massive economic development in these regions. Also, in the developing world, population is tremendously increasing which results to higher energy consumption [6–8]. In addition, as economic development progresses, massive usage and application of gadgets, devices and equipment contribute to the environmental problems. Hence, many of these contribute greenhouse gases (GHG) and ozone layer depleting substances. In fact, air cooling and heating equipment and devices contribute a lot of these gases [9].

As presented by Lund [2], technological innovation for future sustainable energy is necessary. However, its development and implementation is costly as in the case of wave energy [10]. Government support and serious programs are needed if these energy sources should be gradually developed and utilized. Program such as the Global Climate and Energy Project of the Stanford University is good example [11]. As presented in Fig. 2, CO_2 emissions can be reduced through technology development and application. Nandwani [12] shows that minimization of return of investment and maximize the capability of the technologies make it appealing. Hence, for example, combined system such as combined heating and power system (CHP), combined cooling, heating and power (CCHP) system can reduce energy consumption and green house gases emissions [13].

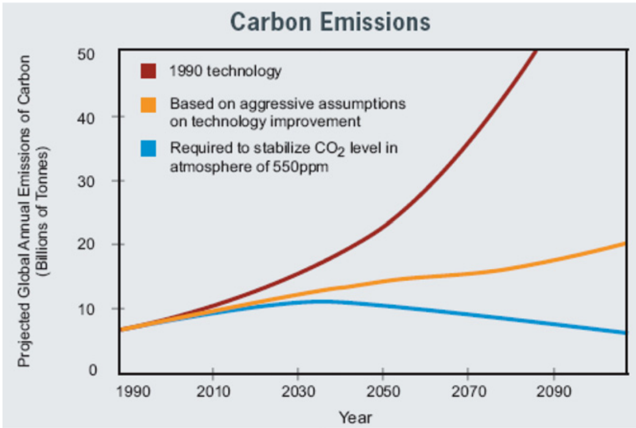

Fig. 2. Reduction of CO_2 emission through clean technology [11].

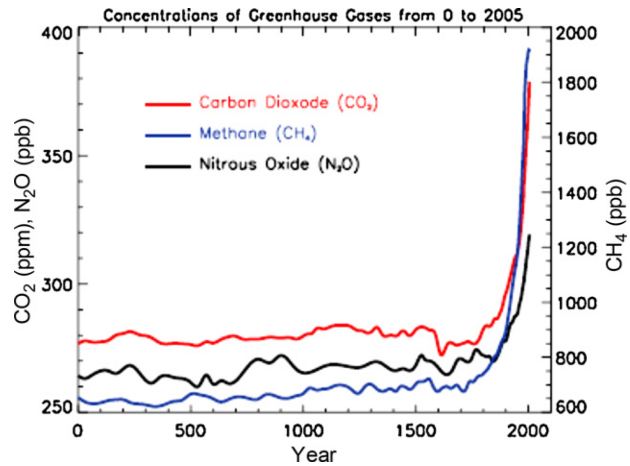

Fig. 3. Atmospheric concentrations of long-lived greenhouse gases [18].

2.1. Conventional energy supply and demand

The energy supply and demand coupled with pollutants emission is one of the greatest threat to human civilization sustainability [1]. Henceforth, the problem of energy supply and demand scenario is becoming serious economically and politically [14]. The conventional energy sources "called carbon-based" are the main source of energy since the start of human civilization. However, the increase of the demand is tremendous during the start of industrial revolution. The carbon-based energy sources (oil, gas and coal) constitute bigger share of the world energy supply. It accounted to 85% according to the report of the International Energy Agency [5,15]. The demand for these energy sources is expected to increase as population explosion, urbanization, and industrialization are happening [16]. The large percentage of the energy supply goes to the developing world which accounted to two-thirds [5].

One of the alarming situations with regard to the supply and demand scenario is the peaking of the supply due to rapid utilization [17]. The scenario also causes instabilities and unpredictability for long term energy supply situation due to the domination of energy supplier from specific region and grouping. Hence, the main source of global conventional energy sources comes from Middle East and Russia. The Middle East accounted for 33% of the world conventional energy supply [5]. In addition, Russian Federation is becoming the global supplier, particularly of natural gas [14]. Due to the above situation, energy and economic politics played. One of the known examples is the 1973 oil crises, Gulf War and Russian-Ukrainian crises [14].

The demands for the conventional energy sources are mostly for the transportation and electric generating plants. The above two accounts for 54% of the total energy demand and expected to increase to 60% in 2030 [5]. The energy consumption for transport industry, household services, agriculture and non-energy uses, will increase 1.6% per year until 2030 according to IEA [5]. The share of electric energy consumption will increase 16% in 2002 to 20% in 2030 based on the report above. The coal-fired power plants generate 45% of the developing world energy requirement and will increase to 47% in 2030. The world gross domestic product (GDP) is expected to grow at 3.2% from 2002 to 2030. The 1% increase of the GDP corresponds to 0.6% increase of the primary energy consumption [5]. As energy consumption is directly related to population size; from present population of 6.2 billion and expected to grow 1% yearly, in 2030, the population size will be 8.1 billion. Migration of population from the rural areas to urban centers will happen and tends to further increase the energy demand [7].

2.2. Environmental problems and conditions

The present environmental condition is complex due to the problems of greenhouse gases emission, ozone layer depleting substances, particulate matters in the air, heavy metals, air chemical and biological contents [18,19]. Fig. 3 shows the increasing greenhouse gases in the air. These large scale emissions of gases and matters in the air due to human activities have detrimental effects to human health and to the civilization sustainability [20]. In the case of air particulate matter such as biological and chemical compounds, they cause health hazard directly [21–23]. Studies show that the global warming and climate change is really due to the large amount of greenhouse gases present in the atmosphere [24].

Since the start of industrial revolution, large amount of greenhouse gases were deposited in the atmosphere [25]. Hence, the increase of global pollutants is due to human activities (urbanization, industrialization, and others) [26]. Greenhouse gases are the primary cause of global warming [27]. The ozone layer depleting substance is the cause of ozone layer thinning [28]. Hence, all of these have consequences to the increase of global temperature which has serious effect to climate pattern–flooding, cyclones, and other weather disturbances [8]. The above situation has serious effect to global sustainability as concluded by numerous studies [29].

With this, alternative approach is needed in confronting massive energy consumption and, large scale greenhouse and pollutant gases emissions [30,31]. Alternative approach such as utilization of alternative energy resources are one of the most prospects [32]. Development of efficient and clean technologies solves the issue of large gases emissions (greenhouse gases and ozone layer depleting substances) [3]. Policies on energy conservation and environmental protections such as renewable energy portfolios are one of the best start-up for tackling this global problem [33].

3. Buildings and provision of human comfort

The building sector (commercial and residential) consumed large percentage of primary energy sources to support its operation and maintenance. Most of this is to support occupants' activities [34]. This is due to the fact that most of the human activities are done in indoor environment—house, office, market, entertainment, and others. Hence, to reduce the building sector energy consumption, several measures address the issue [35].

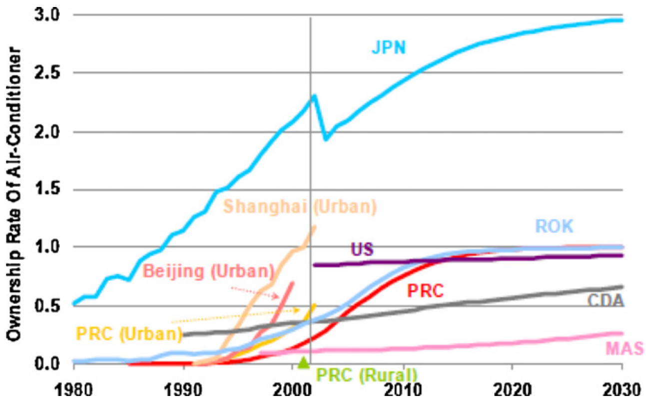

Fig. 4. Rate of ownership of the air-conditioning system in the Asia-Pacific Region [42].

3.1. Building sector energy consumption

As building sector is one of the primary energy consumers accounted to 50% inclusive of commercial and industrial buildings [36]. The sector energy consumption is used to support electrical appliances, thermal comfort and others such as lighting. As global population grows, urbanization taking place, and standard of living becoming higher, it is expected that the building sector energy consumption shall increase [5,7,37]. Study shows that population size and age structure have effects on energy consumption [7]. The sector electric energy consumption will increase by 119% from 2002 to 2030 [5]. The residential sector including the agriculture consumed 56.7% in 2006 compared to 44.2% in 1973 in electric energy consumption [38].

3.2. Building environment conditions

The provision of the human comfort and health conditions consume large amount of the building energy. The energy to support human thermal comfort conditions approaches 50% of the total building energy consumption. In most cases, the energy needed is the high grade electric energy [38]. As most of the electric power generating plants consumed large amount of fossil fuel for power generation, thus, provision for human thermal comfort conditions contributed to the high carbon-based energy consumption and greenhouse gases emissions [5]. Alternative methods therefore, are needed when talking of reducing conventional energy consumption and cutting of greenhouse gases emissions [39]. However, it is imperative not to sacrifice the indoor healthy and thermal comfort conditions for the sake of energy consumption reduction [40,41].

4. Indoor environment cooling and dehumidification

The large part of the energy demand by the buildings is used to support indoor thermal comfort conditions. In commercial buildings, it is almost 50% and varies depending on the location. Approximately there are 368 million installed air-conditioners and heat pumps worldwide [27]. Majority of the market air-conditioners are in the range of 2–700 kW. Most of these marketed air-conditioners are 90% below 15 kW capacity [27]. Fig. 4 shows the rate of ownership of the air-conditioner in the Asia-Pacific Region [42]. Buildings consume large amount of energy to provide indoor human thermal comfort conditions. This electric energy consumption is used either to operate cooling or heating systems. However, in some temperate climates, peaking of electric energy consumption happens in summer as large building energy consumption is shifted to cooling system.

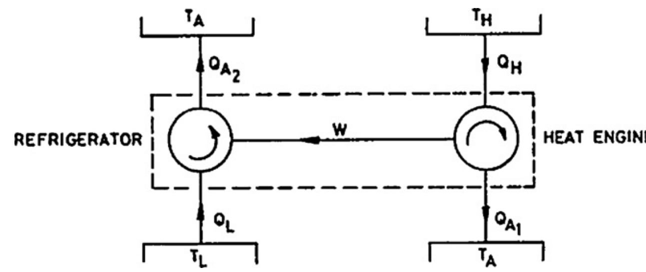

Fig. 5. Thermodynamic principle of the thermal cooling system [51].

4.1. Conventional cooling and dehumidification

The provision of the building indoor thermal comfort conditions either through heating and cooling is done by the heat pumping systems. These devices are widely called the mechanical vapor compression system. Several researches are conducted to improve the system performance through efficiency and lesser environmental damage. However, the system still consumed ample amount of energy in the form of high grade electric energy. The main energy source of the mechanical vapor compression system is the electric energy from the grid line. The system played major role in buildings electric energy consumption most particularly in hot and humid climates. In the Middle East, more than 70% of building energy consumption is to support cooling [43]. In Europe, 10% of the building sector energy consumption is likewise to support cooling demand [44]. In Hong Kong, 45% of the commercial building energy consumption is also for cooling [45]. In Japan, 3% of the building sector energy consumption is for cooling applications [46]. It is expected that in tropical countries which are hot and humid, energy demand for cooling and dehumidification is very high [47].

4.2. Alternative cooling and dehumidification

Alternative air-conditioning system which utilizes alternative materials, processes, and energy resources can largely reduce building energy consumption [48,49]. Building alternative cooling system can be provided with lesser conventional energy consumption through utilization of alternative energy sources and systems [50]. Several active alternative cooling systems are being suggested to provide indoor building cooling [51,52]. These alternatives are jet cooling, absorption cooling, and desiccant cooling. Thermal cooling systems which can be operated through direct thermal energy are important options for building cooling [53]. Hence, solar energy can be utilized for such purposes [54]. The main advantage of these types of system is its cooling load which is in phase with available solar radiation [55]. Hence, during summer time a season of higher solar radiation, the amount of cooling load is also high.

Thermal cooling is done by means of applying heat energy for the production of cooling effect [56]. However, as technologies are varied in operation principles and heat requirements, some thermal cooling technologies have limited applications [57,58]. The main advantage of the thermal cooling system or thermally operated/activated cooling system is the direct application of thermal energy for system operation. Hence, low grade thermal energy can be used to operate the system. In addition, several thermal energy sources can be utilized for the system operation such as waste-heat and others [59]. The concept of thermal cooling is the utilization of higher thermal energy source to drive the cooling system and provide cooling effect. Fig. 5 shows general thermodynamic principle of the thermal cooling system. The concept is based on four temperatures Carnot heat engine [60,61]. However, the thermal cooling system utilizes electric energy for the operation of—fans, pumps and control system. Combined thermal energy and electric energy

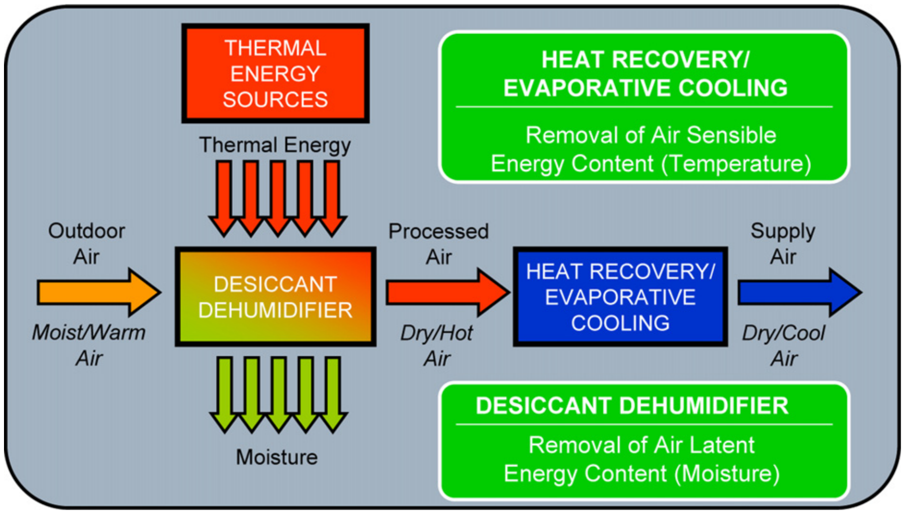

Fig. 6. Basic concept and principle of the desiccant cooling.

can be generated from solar energy through thermo-electric collector (Thermal/Photovoltaic System) [62]. This concept had been done by Mittelman et al. [63] and Kribus et al. [64].

In the thermodynamic point of view, the system performance is dependent on the thermal energy source temperature and on the cooling effect temperature [65]. The system relies on the ambient temperature conditions [51]. Hence, system thermodynamic performance can be obtained based on the system operational temperature conditions [60,61]. The thermally activated/operated cooling systems have wide potential for applications. It is not only applicable for buildings but also to other systems which produce thermal energy (such as waste-heat). Transportation and industrial sectors are the two other sectors with potentials for thermal cooling system. Hence, Mazzei et al. [66] discusses the provision of thermal comfort of the desiccant-based thermally activated cooling system. The system can save conventional energy up to 50% as discussed by Henning et al. [67]. Thus, the system is potential for further development and application through utilization of thermal energy resources and application of the desiccant cooling system.

5. Desiccant cooling principles and concept

The desiccant-based air-conditioning and ventilation system utilizes the capability of desiccant materials in removing the air moisture content by natural process—the sorption process. The sorption process (adsorption and absorption) is an interaction between the sorbent and sorbate molecules through intermolecular interaction. Since desiccant materials have low concentration of water vapor content, the air moisture content is attracted to the surface of the desiccant materials due to the moisture vapor pressure difference between the air and the desiccant surface. In order for the desiccant material to be used again, application of thermal energy is necessary to remove the moisture from the desiccant materials. Fig. 6 shows the basic concept and diagram of the thermally activated desiccant cooling technologies.

5.1. Moisture removal mechanism

All materials that attract moisture at different capacities are called desiccants. Commercial desiccants hold between 10% and 1100% moisture [68]. The commercial desiccants capture moisture until it reach equilibrium condition with the surrounding air and some of which even absorb beyond the air moisture content. The removal of moisture from the desiccant can be done either by heating or by reducing the pressure. In commercial application, heating is the most preferred method, while the industrial processes; reducing pressure is the preferred one.

The adsorption is a surface phenomenon occurring at the interface of two phases, in which cohesive forces including the Van der Waals forces and hydrogen bonding act between the molecules of all substances irrespective of their state of aggregation [69]. The process is called physisorption. Absorption is a chemical process caused by the valency forces called chemisorption [70].

The process of attracting moisture from the air is either by adsorption or by absorption: the adsorption process is a physical process in which the property of the desiccant material remains the same; while in the absorption process, upon attracting moisture, the physical characteristic of the material changes.

The desiccant materials can be either solid or liquid: the solid desiccant and hydrophilic adsorbents are the silica gel, activated alumina, zeolites and except for the calcium chloride which is absorbent. The commercial hydrophobic solid adsorbents are the activated carbons, metal oxides, specially developed porous metal hydrides and composite adsorbents [69].

Some desiccant materials are combinations of absorbent and adsorbent to enhance its physical properties and sorption capacity called composites [71]. The basic mechanism in the sorption of moisture between the air moisture and of the desiccant material is the difference in the water vapor pressure in the surface of the desiccant and of the material. The uptake of moisture from the air to the desiccant is when the vapor pressure in the air is high; the removal of vapor from the desiccant material is done when the vapor pressure in the air is lower than on the desiccant material. When the vapor pressure is the same both in the air and in the desiccant material, the equilibrium condition is reached and sorption process stopped. The only means to make the adsorption process proceed is by using outside forces such as by increasing the air pressure, decreasing the temperature or by artificial electromotive force [70]. The same procedure is applied for the removal of moisture from the desiccant material which is done in opposite way.

In industrial applications, the sorption process based on the changing of pressure is called *pressure swing* process and is most common in gas purification processes. In commercial application, operation of desiccant process is done through the changing of the temperature which is called *temperature swing* process.

The desiccant cooling technology resource guide developed by the US Army Construction Engineering Research Laboratories

[72] shows the many applications of the desiccant cooling from the planning, programming, budgeting, design and engineering guide, construction, operation, management which can be applied in civilian buildings. Desiccant cooling system relies on desiccant material in controlling air moisture content both for air cooling and dehumidification. The desiccant material reduces the air moisture passing through it by either application of evaporative cooling or by other means of air cooling.

5.2. Air cooling processes

The air after passing the desiccant material is dry and hot due to the conversion of air latent energy to sensible energy, release of heat of sorption in the case of solid desiccant cooling, and the heat carry-over from the regeneration side to the process side. There are several air cooling processes for the reduction of air sensible energy contents (temperature). Natural processes such as the evaporative cooling, heat exchanging with cool water and application of heat pumps (hybrid system) are done for the air.

The most widely used air cooling in the desiccant cooling system is the application of the evaporative coolers [59,67,73–77]. These coolers can be applied directly (addition of moisture) or indirectly (use of secondary air for sensible heat exchange with primary air). There are many designs and application of the direct evaporative coolers. Hence, it is widely applied in the desiccant cooling system. Other natural air cooling can be done through heat exchanging with cool ground water. The ground water temperature is cooler than tap water. Heat exchanging it with the air from the desiccant material can reduce the air temperature. In addition, application of other cooling devices such as absorption chillers and vapor compression system and other available cooling devices can be used for the cooling of air. The main advantage of the cooling of air using the available cooling system (heat pump and chillers) is it can be operated above the dew point temperature of air. Thus, its coefficient of performance is increased since it operates at higher temperature [78].

5.3. Air dehumidification and cooling

The air dehumidification by desiccant materials and air cooling by means of evaporative cooling process or other means separate the handling of air sensible and latent energy contents. Thus, with the process, different energy sources can be used to handle the air sensible energy and latent energy. In the ordinary heat pump, the handling of the air two thermal loads is done in the same process, thus, the performance of the system is reduced due to the excessive utilization of energy from a single source.

The desiccant cooling system separate the handling of air latent energy from the sensible energy with the application of desiccant material in removing air moisture by natural process—sorption process. On the other hand, the reduction of air sensible energy content can be done in many different ways. In the case of the natural methods, evaporative cooling and ground source cool water can be used for air cooling. On the other hand, heat pumps and sorption chillers can be used to cool the air. Hence, with this method, its performance is increased due to its operation at higher temperature—above the air dew point temperature. Thereof, the desiccant cooling system is the promising cooling and dehumidification methods which can utilize different sources of thermal energy—either from renewable energy sources, non-conventional energy sources or from system combining heat and power production.

The main advantage of the desiccant cooling system is the separate handling of air sensible and latent loads. Hence, in the case of latent load, desiccant material can handle it through the application of thermal energy. In the case of the sensible load, heat recovery, direct evaporative cooling, and other air cooling can be applied. Thereof, for hot and humid air with latent load which is high, potential for reduction of conventional energy (electric energy) is possible. Even though there are several issues arising from the wide applicability of the desiccant cooling system, the system is presently applied in different climatic conditions.

6. Solid desiccant cooling

The solid-based system uses solid desiccant materials in the removal of air moisture content. There are several kinds of solid desiccant materials—silica-gel, titanium silicates, calcium chloride, activated aluminas, zeolite (natural and synthetic), molecular sieve, lithium chloride, organic-based desiccants, polymers, compound and composite desiccants.

6.1. Concept and operation

The solid desiccant cooling system is primarily based on the application of solid-based desiccant materials in controlling air moisture content. The sorption mechanism in the solid material is either through absorption or adsorption. Cooling by means of heat recovery, evaporative cooling or other means are applied to the system.

The design of the system is based on the fixed bed type in alternative operation of moisture sorption and desorption. Application of the encapsulated phase change materials (EPCMs) in the desiccant bed had been applied. The purpose of this is to absorb the heat of sorption released during the dehumidification process. Based on the study, it lowers the air temperature. However, its humidity is higher compared to the pure desiccant [79]. For building cooling application it is done through temperature compared to industrial applications of pressure. The processed air (dehumidified air) is pre-cooled through in most cases the rotating heat wheel through either utilization of the cool return air or by means of the outside air. As the air in most cases is still warm for application indoor, air final cooling is done by means of evaporative cooling, chill cooling.

The solid desiccant cooling system is the most widely used desiccant cooling system. This is due to the simple handling of desiccant materials. The desiccant material is typically impregnated to the honeycomb designed wheels or of the cross-flow heat exchangers. Although, typical solid desiccant materials have higher regeneration temperatures than the liquid desiccant, new researches made new materials with lower regeneration temperature requirements.

6.2. Development and evolution

6.2.1. Desiccant wheel type

Solid desiccant cooling system is simpler to use and apply due to the easy handling of the desiccant material. Hence, the system is not complicated unlike the liquid desiccant cooling system in design and operation. Farooq and Ruthven [80], investigated the desiccant bed for solar air conditioning application. The study shows that the optimal choice of desiccant can be compensated by the appropriate adjustment of the cycle time. In addition, cost in making desiccant wheel and moisture diffusivity be given consideration. Jurinak et al. [81] presented the open cycle desiccant cooling system both for ventilation cycle and recirculation cycle. It shows that unbalancing the air flow through the dehumidifier improved the desiccant system COP of 10–15% for ventilation cycle and to 50% for recirculation cycle. To make the desiccant cooling system competitive, thermal COP of the high-performance desiccant systems must be improved to be competitive with the conventional vapor compression system such as very high heat and mass transfer unit dehumidifier with large thermal capacitance matrix. The most common solid desiccant cooling system is composed of the two wheels type or called the Munter Cycle shown in Fig. 7. This is the basic design of the

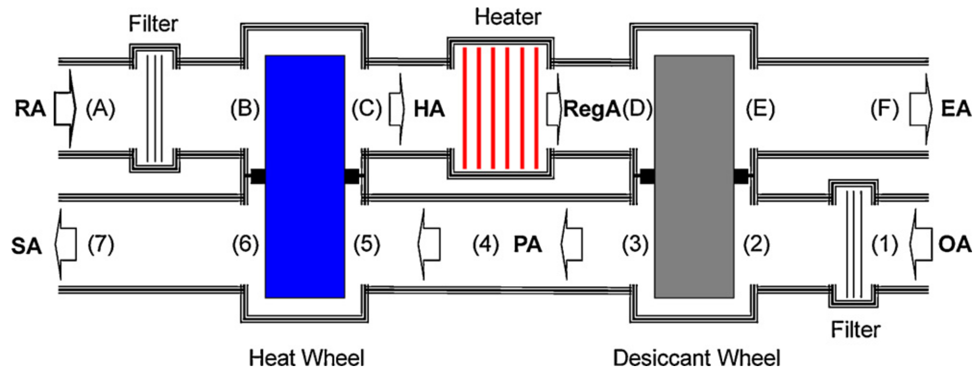

Fig. 7. The double wheels type desiccant cooling [90].

solid desiccant cooling system. Application of the air cooling done in both the supply air and in the return air is implemented. Hence, several modifications of this cycle implementing different strategies of operation such as presented by Henning et al. [59] and Jain et al. [82].

The application of the desiccant wheel as the air dehumidifier has factors to be considered. Kang and Maclaine-cross [83] shows the performance of the desiccant-based cooling and dehumidification system relies much on the desiccant material in moisture sorption capacity. Kodama et al. [84] shows that there is an optimal speed by which high sorption rate exists in the rotating desiccant wheel. The optimal speed increases with increasing regeneration air flow rate, decreasing desiccant wheel depth, and decreasing bulk density of rotor. The optimal wheel speed decreases with higher humidity and lower regeneration temperature. It shows also that the sorption rate is relative to the air relative humidity. Zhang and Niu [85] shows that the sorption performance of the desiccant wheel depends on the wheel rotational speed and the number of the transfer units. Hence, it was suggested that desiccant wheel should have number of transfer units of 2.5. Subramanyan et al. [86], shows that increasing the air flow rate reduces the specific cooling load (difference in the enthalpy of the outdoor air and of the processed air). The cooling load increases due to the amount of air mass flow rate. In addition, Subramanyan et al. [87], shows that increasing the air flow rate, increases the supply air moisture content. Harse et al. [88] shows that for higher humidity air, the optimal speed of the wheel is greater than for the air with lower humidity content. It shows that for higher regeneration temperature, the performance of the desiccant wheel improved. The depth of the wheel affects the dehumidification rate—as the depth increases, dehumidification rate increases resulting to lowering of the optimum wheel speed. Gao et al. [89] shows that the thickness of the desiccant material affects the sorption capacity. At higher desiccant material thickness in the channel, higher sorption rate is attained due to more time to reach the steady state. In addition, lower desiccant rotor speed is made for optimum wheel speed. The study shows that channel shapes affect the rotor sorption capacity. Hence, for the same cross sectional area, sinusoidal channel is the best performer due to its lower hydraulic diameter resulting to higher air velocity and heat transfer coefficient. Furthermore, the study shows that increasing the outdoor air relative humidity increases the processed air temperature. However, the humidity content of processed and of the exit air increases as relative humidity of the outdoor air increases. Enteria et al. [90] presented parameters affecting the performance of the desiccant wheel and performance evaluation for the desiccant wheel dehumidification capability. La et al. [91] presented the review of the development of the rotary desiccant wheel based system.

6.2.2. Fix bed type

The fixed bed solid desiccant cooling system is another type of the system. Studies had been conducted on the system. The advantage of the bed system is the sorption process which can be done through isothermal way. It means that the air after passing the desiccant material, its temperature is not increased. Hence, the sorption process is increased due to the removal of heat of sorption. Yuan et al. [92] proposed a cross-cooled compact solid desiccant dehumidifier. The aim of the design is to make the dehumidification process cooler due to the heat exchange between the dehumidified air and the secondary air. It was shown in the result that the performance of the design is better than without secondary cooling. Majumdar and Worek [93] investigated the open cycle cooled-bed desiccant cooling system using the cooled bed dehumidifier. It shows the system performance is more sensitive to the regeneration and indoor temperature and to the outdoor humidity ratio than to the indoor humidity ratio and outdoor temperature. It shows that the cooled-bed system can be regenerated at low temperature of 50 °C. Fig. 8 shows the cross-flow fixed bed type air-dehumidifier with cooler. Henning [57] shows the application of fixed bed through cyclic operation called evaporative cooled sportive heat exchanger (ECOS).

6.2.3. Modified types

In most design, the operation of solid desiccant cooling system is through dehumidification-humidification process. With such process, air dehumidification is done at very low humidity content for the application of evaporative cooling. With such process, the required regeneration temperature is increased. Thereof, constant dehumidification process is another option to avoid the deep dehumidification which will be applicable to hot and humid climate.

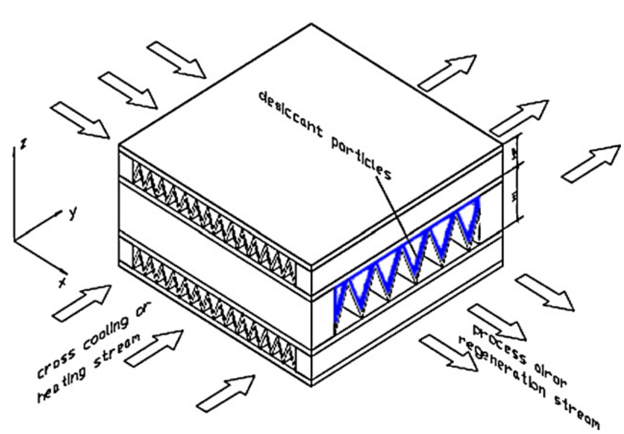

Fig. 8. Desiccant coated cross-cooled compact dehumidifier [92].

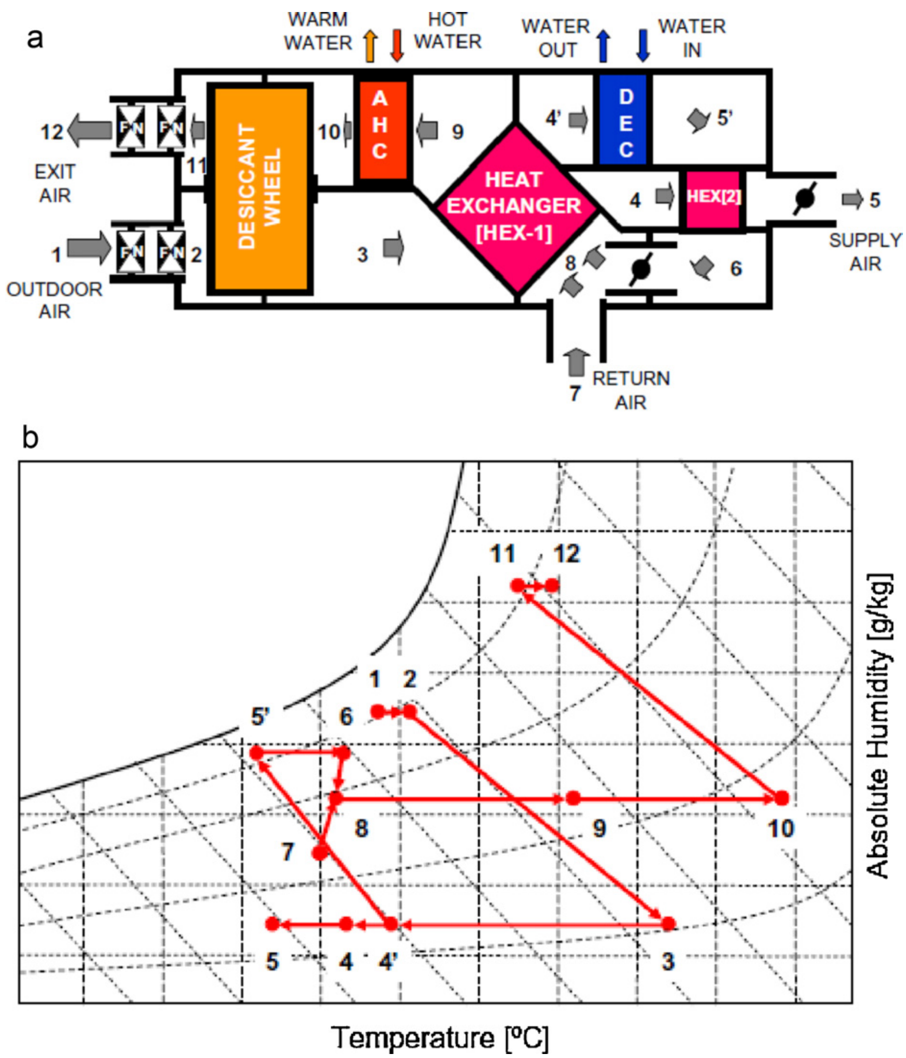

Fig. 9. Constant humidity supply air desiccant cooling system [94].

Enteria et al. [94] and Enteria et al. [95] presented the constant humidity air cooling cycle of the desiccant as presented in Fig. 9. Ando et al. [77] shows the double stage dehumidification process. In the double stage dehumidification process, two desiccant wheels are employed (Fig. 10). The main purpose of the double stage dehumidification is to reduce the air moisture content in the case of humid air with lower regeneration temperature requirements. Ge et al. [96] investigated the two-stage desiccant cooling system. It shows it has lower regeneration temperature requirements with higher COP. Kodama et al. [76] shows the multipass desiccant wheel shown in Fig. 11. It shows 50 °C regeneration temperature is enough for the desiccant wheel. Furthermore, Kodama et al. [97] presented several designs of the desiccant cooling system for humid climates. It shows that the 4 wheel cycles (two desiccant wheels and two heat wheel) can be used for the climatic condition. In addition, the 3-wheel cycle (1 desiccant wheel, 1 heat wheel and 1 total heat exchanger) is better than the 4-wheel cycle.

6.3. *Application and evaluation*

6.3.1. *Temperate climate*

The solid based desiccant cooling system had been actually applied in many different climatic conditions. In addition, feasibility studies through numerical studies had been done about the applicability of the system. White et al. [98] conducted numerical investigation of the solar powered desiccant cooling system in different Australian climatic conditions. The investigation centered in direct application of solar energy for the regeneration of the desic-

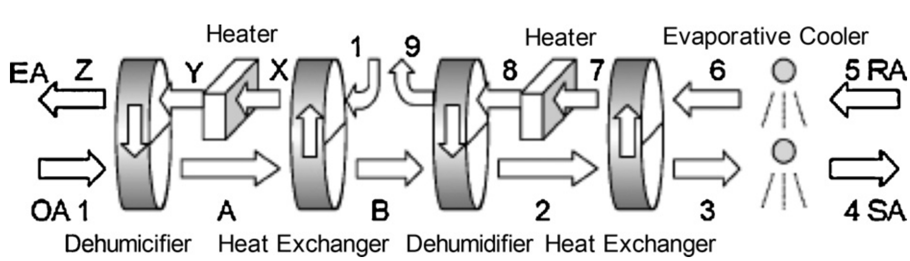

Fig. 10. Double stage dehumidification desiccant cooling system [77].

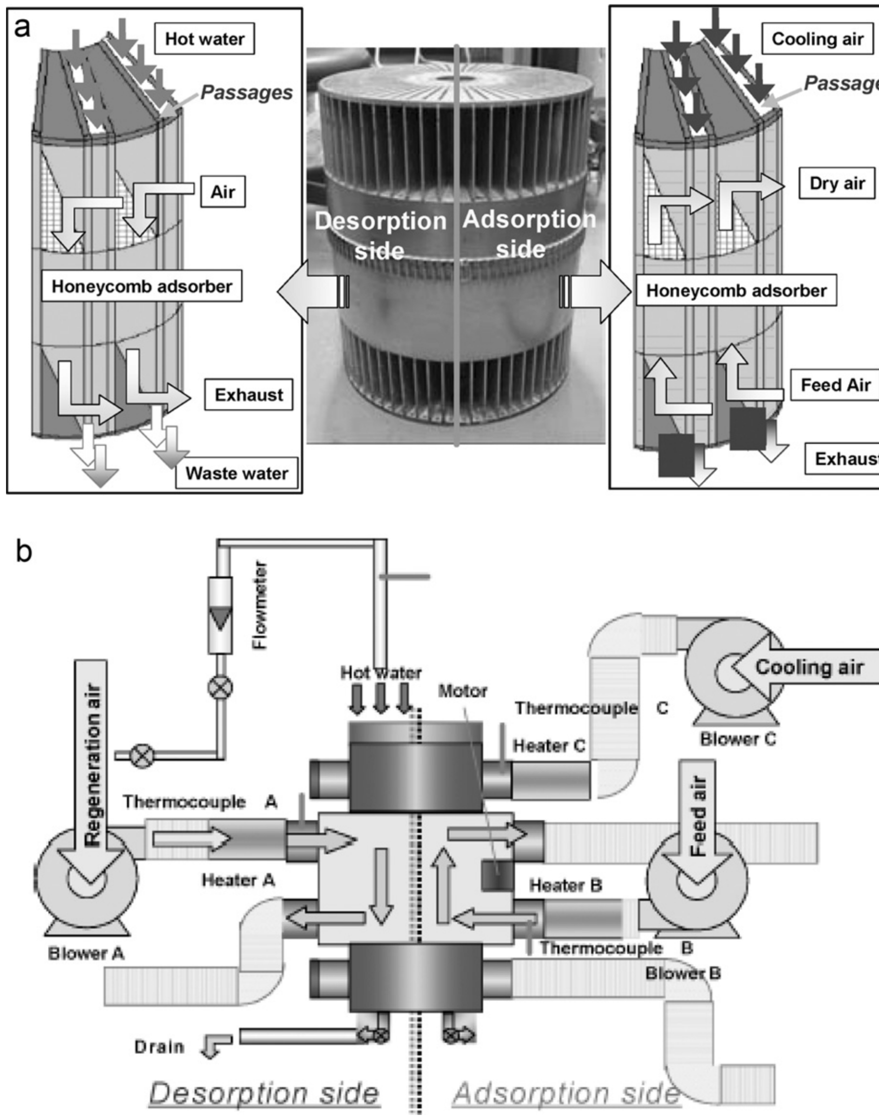

Fig. 11. Principle and diagram of the multipass desiccant wheel [76].

cant wheel. The investigation shows that the system is applicable in the warm temperate climate of Melbourne and Sydney; however, in the tropical climate of Darwin it is inapplicable due to the hot and humid outdoor air. It shows that solar energy can support the building comfort condition by means of high ventilation rate. Bourdoukan et al. [99] conducted numerical investigation of the solar powered desiccant cooling system using evacuated tubes collector. It shows that collector areas vary with different location due to the required cooling load. For higher outdoor air humidity content, higher solar collector area is needed as compared in three geographical locations (La Rochelle-France—13.4 g/kg, Bolzano-Italy—11.4 g/kg, Berlin-Germany—9.5 g/kg). Furthermore, it shows that evacuated tube is better than the flat plate collector due to the small required back-up thermal energy. Sand and Fischer [100] investigated the application of the solid desiccant system with package of HVAC equipment. It shows that the active desiccant module delivers the required air condition with lower cost. Henning et al. [67] conducted investigation with regard to the application of solar desiccant cooling in Europe. It shows the possibility of simple design of desiccant cooling system totally dependent on solar energy. However, the condition of the indoor air sometimes exceeds the required level. The climate to which the system is applicable is in the temperate climate. Further solar desiccant with chiller is feasible in terms of economic and energy point of view in the warm-humid climate in which energy saving of 50% is possible. Mavroudaki et al. [101] presented a numerical investigation with regard to the application of single stage desiccant cooling system in European cities. The result shows that the system is applicable in some parts of southern Europe as long as latent load is not high. This is due to the high regeneration temperature requirement for high relative humidity air. The system is feasible in most of central Europe. Atlantic and inland regions of southern Europe appear to be much more suitable to this technology than the Mediterranean costal regions. Smith et al. [102] investigated the application of solar powered solid desiccant cooling system in residential buildings in United States through Transient System Simulation (TRNSYS) simulation. The study focused in the Pittsburgh, MA, Macon, GA, Albuquere, NM. It shows that building cooling demand was met. It shows that solar energy is suited in the operation of desiccant in the southwest with 72.7% of energy from solar. While 18.0% of desiccant cooling provided by solar energy for the southeast. Casas and Schmitz [103] investigated the application of borehole heat exchanger in the desiccant cooling system with gas engine (Fig. 12). The system is installed in the demonstra-

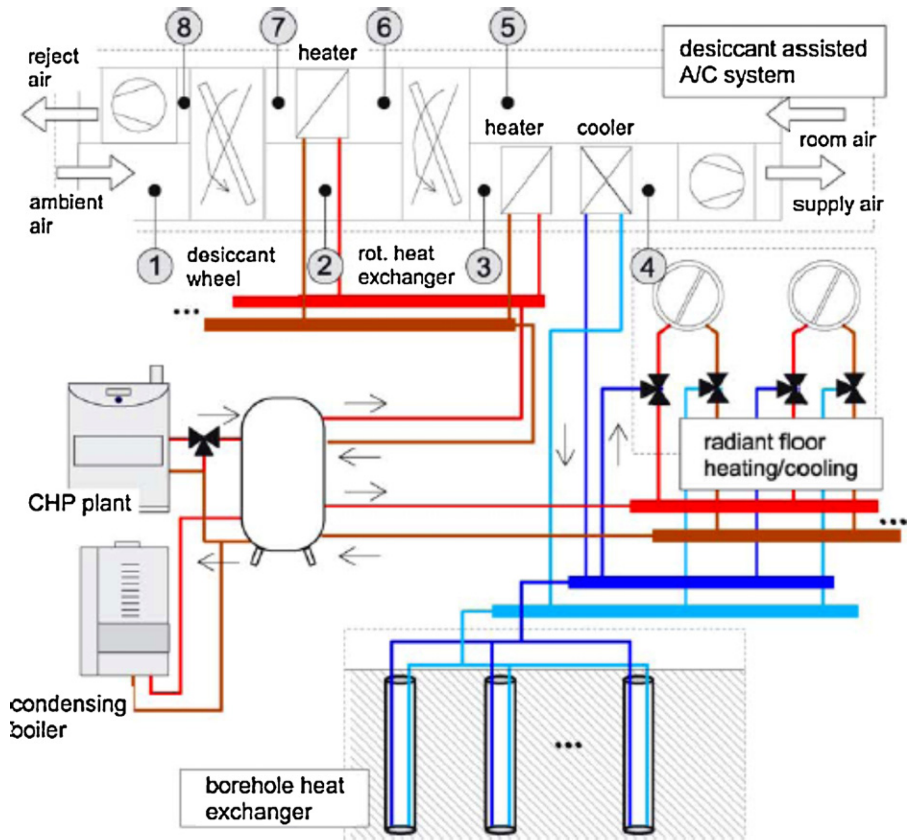

Fig. 12. Desiccant assisted HVAC system with borehole heat exchanger [103].

tion building. It shows the system save 70% of energy for desiccant with borehole heat exchanger. In the case of desiccant with chiller, it can save to 30%. Cler [104] investigated the possibility of applying desiccant dehumidification in military facilities. It shows that it is recommended when additional cooling capacity is needed in existing HVAC system. Also, for higher quantities of outdoor air make-up, desiccant-based system is ideal for this type of applications. In new construction, desiccant dehumidification equipment should be considered. This would reduce the size of chiller and electric energy demand, in addition, when designing new desiccant cooling system, desiccant regeneration from vapor compression, solar energy, cogeneration and others should be considered in early phase of design. Halliday et al. [105] investigated the feasibility of applying solar desiccant cooling system in UK. It shows that the solid desiccant-solar power is feasible for application in buildings as long as proper manner is applied in the system. Henning et al. [59] shows the application of desiccant cooling system in tri-generation system (power + heating and cooling). It uses the vapor compression chiller and silica gel desiccant with the electricity to drive the chiller coming from the CCHP while the regeneration of the desiccant wheel from the waste-heat from the CCHP. It shows an electric saving of more than 30% compared to the conventional air handling system.

6.3.2. Sub-temperate and sub-tropical climates

Fong et al. [106] conducted investigation with regard to the application of solar desiccant cooling system in the subtropical climate of Hong Kong. Although, typical desiccant cooling system is not energy efficient, it can supply the required fresh air to the building resulting to the good indoor air quality and ventilation effectiveness. Hao et al. [107] investigated the application of the desiccant dehumidification with chilled ceiling and displacement ventilation. It shows it is feasible to be applied in the hot and humid climate due to its capability to respond consistently to cooling demand. In addition it reduces building energy consumption to 8.2% compared to conventional system. Niu et al. [108] investigated the application of the desiccant dehumidification by desiccant wheel with chilled-ceiling (Fig. 13). The aim of the installation is for the desiccant to reduce the air moisture content and thus avoid the condensation of moisture in the ceiling panel and at the same time cool the air by means of the chilled-ceiling. The results show the combined system can save up to 44% of primary energy consumption in which 70% of the operating hour of the desiccant dehumidification can be provided at lower grade of regeneration air of less than 80 °C.

6.3.3. Hot and humid climates (tropical, middle east and Mediterranean)

Khalid et al. [109] conducted numerical investigation with regard to the application of solar desiccant cooling in Pakistan climatic conditions. It shows the system has higher COP in Lahore climatic conditions without auxiliary cooling. Hirunlabh et al. [110] investigated the applicability of the solid fix-bed desiccant cooling in the hot and humid condition of Thailand. It shows that it can save 24% of electric energy. Furthermore, it is practical for application in large buildings and centralizes air-conditioning system. Nagaya et al. [111] investigated the application of the solid desiccant wheel in the automobile air-conditioning system (Fig. 14). It shows that the system is energy efficient compared to the conventional system. One of the problems encountered is the difficult control of the air humidity and temperature due to the heat exchange and coolant flow to the evaporator. Camargo et al. [112] investigated the application of the solid desiccant cooling system in Latin America and in tropical and equatorial cities. It is composed of the desiccant

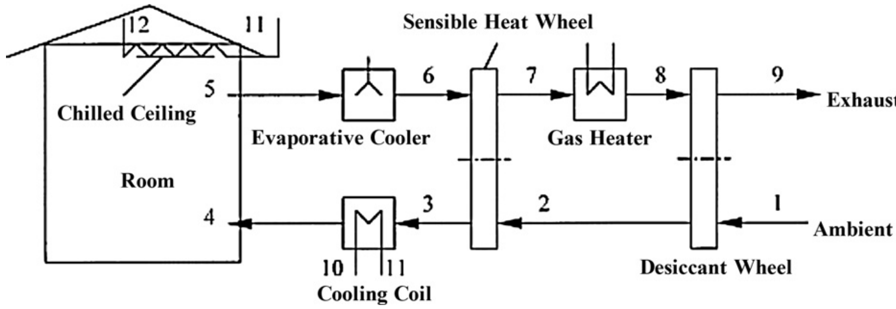

Fig. 13. Chilled-ceiling with desiccant cooling [108].

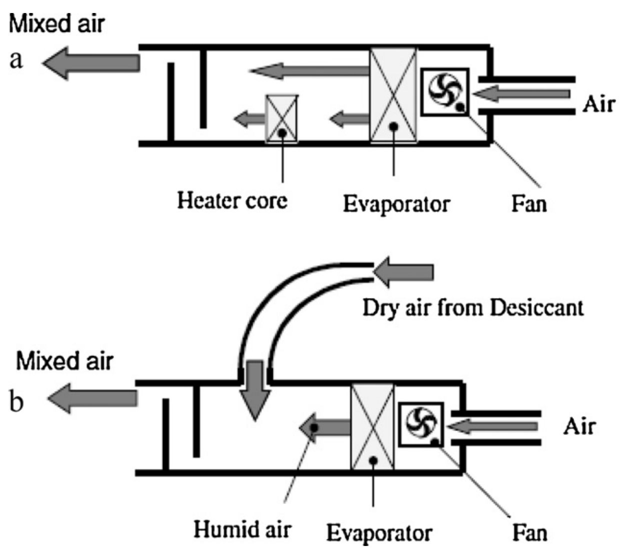

Fig. 14. Automobile air conditioning system: (a) conventional and (b) with desiccant [111].

wheel and evaporative cooler. The result shows the applicability of the system as alternative to the vapor compression system since it can provide human thermal comfort conditions. Dupont et al. [113] investigated the applicability of the silica compact bed desiccant cooling system powered by solar energy. The investigation was carried out at the tropical climate of Guadeloupe. It shows that is can produce cooling power. However, the system is not efficient due to losses'. Hamed [114] investigated the packed porous bed with burned clay as desiccant carrier and impregnated with liquid calcium chloride as desiccant. It shows that the mass transfer rate has significant effect on the concentration gradient in the bed. Jain et al. [82] investigated the solid desiccant cooling system for hot and humid climates in 16 Indian cities. It shows that cycle with wet surface heat exchanger gives higher coefficient of performance (COP) than other cycles. Dunkle cycle has been found to be better at all climatic conditions. Heat exchanger effectiveness of above 0.8 is desirable for better performance of the cycles not using wet surface heat exchanger. The effect on COP of the evaporative cooler is insignificant but it can control the room sensible load factor. Joudi and Madhi [74] investigated the applicability of the solar desiccant cooling system in Basrah, Iraq (Fig. 15). For the local weather condition, it shows that a regeneration temperature of 70 °C can be provided using solar energy at clear sky. Kabeel [115] investigated the application of the calcium chloride desiccant wheel constructed from the iron wire and clothes layer. The system use sole solar energy for the regeneration of the desiccant. The system is tested in Egyptian climate which has high performance after solar noon and the wheel effectiveness depends on solar radiation and air flow rate.

7. Liquid desiccant cooling

The liquid desiccant cooling system utilizes the liquid desiccant in controlling air moisture content. The process of air moisture reduction is through absorption process. Upon reduction of the air moisture content, the air is passed in the same way as in the air cooling done in the solid desiccant cooling system.

7.1. Concept and operation

The design of the liquid desiccant cooling system is using the falling film type in the membrane with air passing to its surface

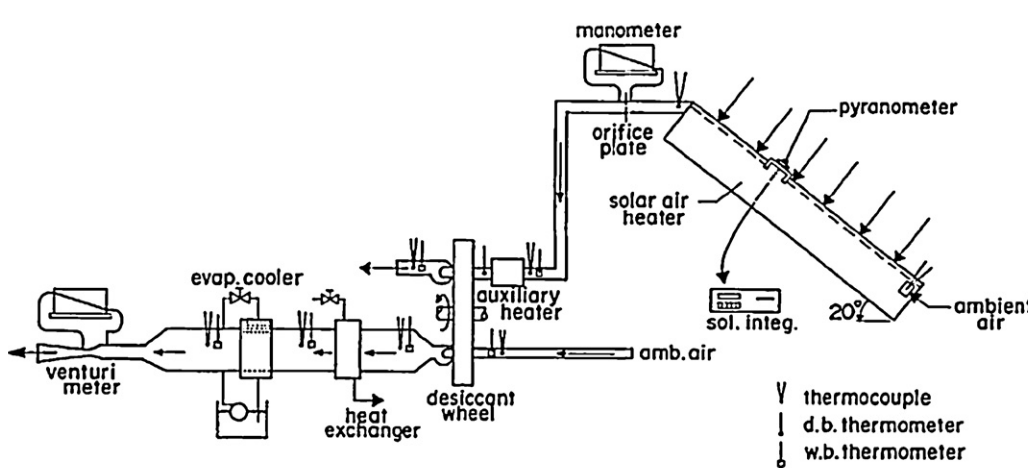

Fig. 15. Solar-desiccant system [74].

[116]. Some designs apply the spray type to increase the surface area of air-desiccant contact. The design of the air dehumidifier can be done with isothermal process by passing cool air/water at the back of the falling desiccant film [117]. The regeneration of the desiccant material is by means of heat. Hence, many designs of the liquid desiccant regenerators are done with solar energy. The cooling of air after the desiccant material is in the same ways as in the solid desiccant cooling systems. The liquid-based system utilizes liquid desiccant materials in removing air moisture content. The widely used liquid desiccant materials are the lithium chloride, lithium bromide, calcium chloride and glycol-based substance [51]. Also, the application of these materials depends on the cost, operations, and the source of thermal energy. In addition, some liquid desiccants are corrosive, and require proper handling in their application. However, the main advantage of the liquid desiccant is the high moisture removal capacity with lower regeneration temperature requirement.

Liquid desiccant cooling system relies on the liquid desiccant in controlling air moisture content. The process of liquid desiccant control of moisture is by means of absorption process. One of the main advantages of the liquid desiccant cooling system is the lower regeneration temperature requirements and lower thermal and chemical storage. The advantage of the hybrid desiccant cooling system is the complete operation of the system using electric energy at higher performance. Means, for small applications, hybrid desiccant cooling system will prevail more than the pure desiccant cooling.

7.2. Development and evolution

Liquid desiccant cooling system has the advantage of lower regeneration temperature with higher moisture sorption capacity than the solid desiccant cooling system due to the higher moisture mass transfer area. One of the major concerns of the liquid desiccant cooling system is the carry-over to the supply air. Hence, several studies had been done on the issue. In addition, liquid desiccant materials are corrosive and simple handling of the working media is difficult and needs special materials. However, advancement in the field is fast which resulted to some applications with potential market share.

7.2.1. Typical design

Alizaldeh and Saman [118] investigated the direct solar collector and desiccant regenerator. It shows that water loss rate generally decreases with increasing solution mass flow rate. It is also applicable to the Adelaide summer conditions. Factors such as initial air temperature and solution temperatures, solar insulation and ambient air ration may affect the performance. Kabeel [119] studies the regeneration of the liquid desiccant through the application of solar collector. It shows the enhancement of the regeneration for the forced flow compared to the natural flow. This is due to the increase of the mass transfer coefficient. Fumo and Goswami [120] investigated the packed tower lithium chloride desiccant system. It shows that the main factors affecting the dehumidifiers are the desiccant concentration, desiccant temperature and air-humidity. In the case of the regenerator, it shows that desiccant temperature, desiccant concentration and air flow rate are the factors. Other factors influencing the performance are the mass flow of air with respect to desiccant solutions. Gandhidasan [121] investigated the air dehumidification with liquid desiccant. It shows that the cooling of desiccant prior to the dehumidifier using water from cooling tower affect the dehumidification rate. At lower cooling tower water temperature, the rate of moisture removal increase. In addition, the heat exchanger effectiveness affects the dehumidifier performance. Lazzarin et al. [122] investigated the liquid desiccant system with water and lithium bromide solution and water and calcium chloride solution.

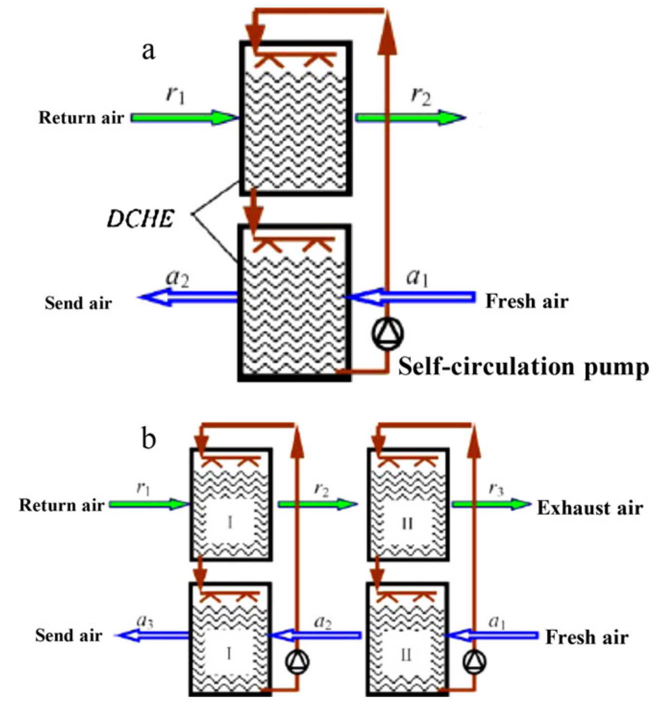

Fig. 16. Liquid desiccant total heat exchanger: (a) single stage and (b) double stage [123].

7.2.2. Innovative design

Li et al. [123] introduced the design of the liquid desiccant total heat exchanger shown in Fig. 16. The simulated EER (energy efficiency ratio for the air processor is 6.3–7.3 in summer condition. Liu et al. [124] presented the design of the liquid desiccant cooling system. Tu et al. [125] proposed a liquid desiccant cooling system. The system employed lithium chloride desiccant. It uses indirect and direct evaporative cooling to reduce the process air temperature. Xiong et al. [126] investigated the two stage hybrid desiccant cooling system using the lithium bromide as the primary dehumidifier assisted by the calcium chloride powered by solar energy (Fig. 17). The results show the improvement of the energy storage capacity compared to the ordinary liquid desiccant system, also, better dehumidification performance due to the effect of pre-dehumidification. The performance of the system is higher than the ordinary liquid desiccant by 15.8% and 32% (TCOP and COP). The cost of the liquid desiccant sections decreased by 5% as long as there is abundant solar energy source. Yin et al. [117] presented a novel liquid desiccant regenerator/dehumidifier. The design is based on the plate fin heat exchanger (PFHE) shown in Fig. 18. During the internally cooled dehumidification, the desiccant efficiency decreased with the increase of water temperature. It shows that the internally heated regeneration efficiency is better than the adiabatic regeneration. Li and Yang [127] investigated the solar powered liquid desiccant cooling system. In the application to Hong Kong climate, it shows a 25–50% of energy saving compared to the vapor compression system. In addition, the higher the latent load in the total ventilation load, the higher the energy saving. Badami and Portoraro [128] investigated the small tri-generation plant with liquid desiccant cooling system as shown in Fig. 19. It is coupled to the small gas-fired internal combustion engine from which the flue gases and engine cooling water are recovered for liquid desiccant operation. It shows that the desiccant cooling is a possible alternative to other technical solutions including the economic point of view. Kessling et al. [129] investigated the liquid desiccant cool-

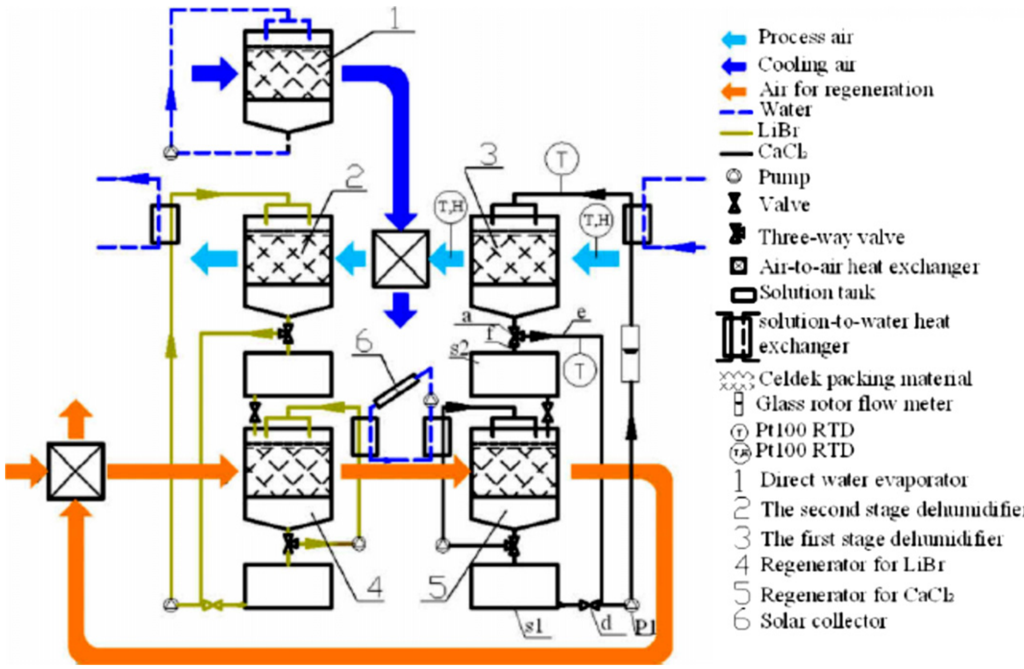

Fig. 17. Solar two-stage liquid desiccant based hybrid system [126].

ing system with thermal storage (Fig. 20). The important factors for efficient absorption process are the inlet concentration of the liquid desiccant and the temperature during the absorption process. For a high energy storage capacity, high ratio of air to solution is required to achieve great difference between the solution inlet and outlet concentration ratio. Khan and Matinez [130] numerically investigated the performance of the liquid desiccant absorber. It shows the performance of the absorber depends on the physical size of the absorber, solution concentration, and cooling process air mass flow rates. Furthermore, the study shows that the counter flow and parallel flow absorbers have no performance difference. The effectiveness varies greatly with the number of mass transfer units between the processed air and the desiccant solutions. Oliviera et al. [131] investigated the air fan with fiber impeller which is wetted with liquid desiccant solution shown in Fig. 21. It shows the system have lower initial cost than the wheel due to the lower system size and volume. This is due to the higher heat and mass transfer area in the needle of the impeller motor. Pietruschka et al. [132] investigated the liquid desiccant absorber with heat exchanger (Fig. 22). The advantage of the heat exchanger absorber is the combined air dehumidification and cooling which makes the absorption process efficiency high. Saman and Alizaldeh [133] investigated the combined heat exchanger and liquid desiccant absorber. It shows the heat exchanger performed with the liquid desiccant absorber. In addition, at 45° inclination angle, it has an optimum air mass flow in which the heat exchanger effectiveness and dehumidification effectiveness are at a maximum. Hence, at 45° angle, the heat exchanger performs well as a dehumidifier/indirect evaporative cooler. Furthermore, it shows the performance depends on the physical size, number of transfer units both in water side and

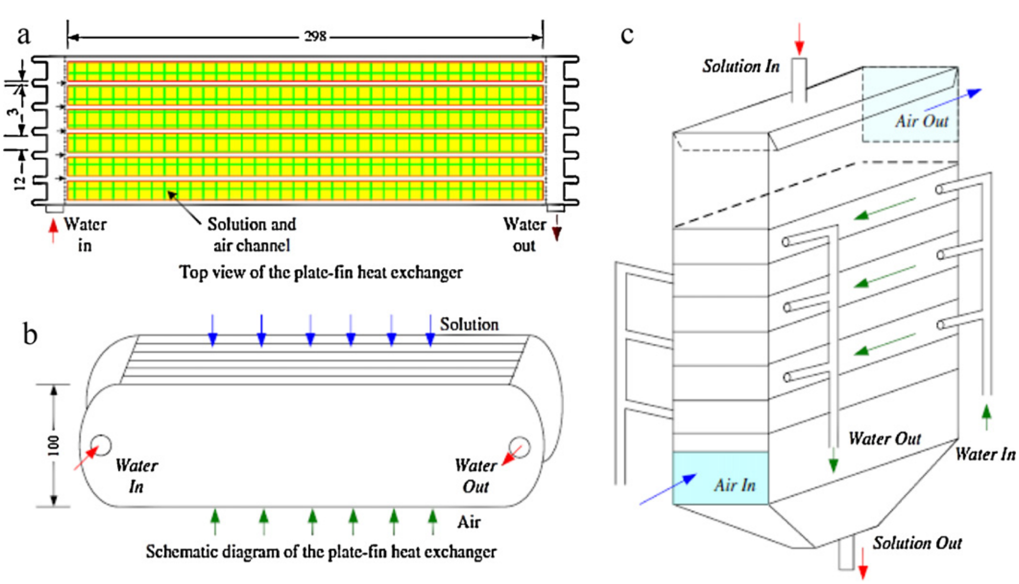

Fig. 18. Internally cooled/heated dehumidifier/regenerator [117].

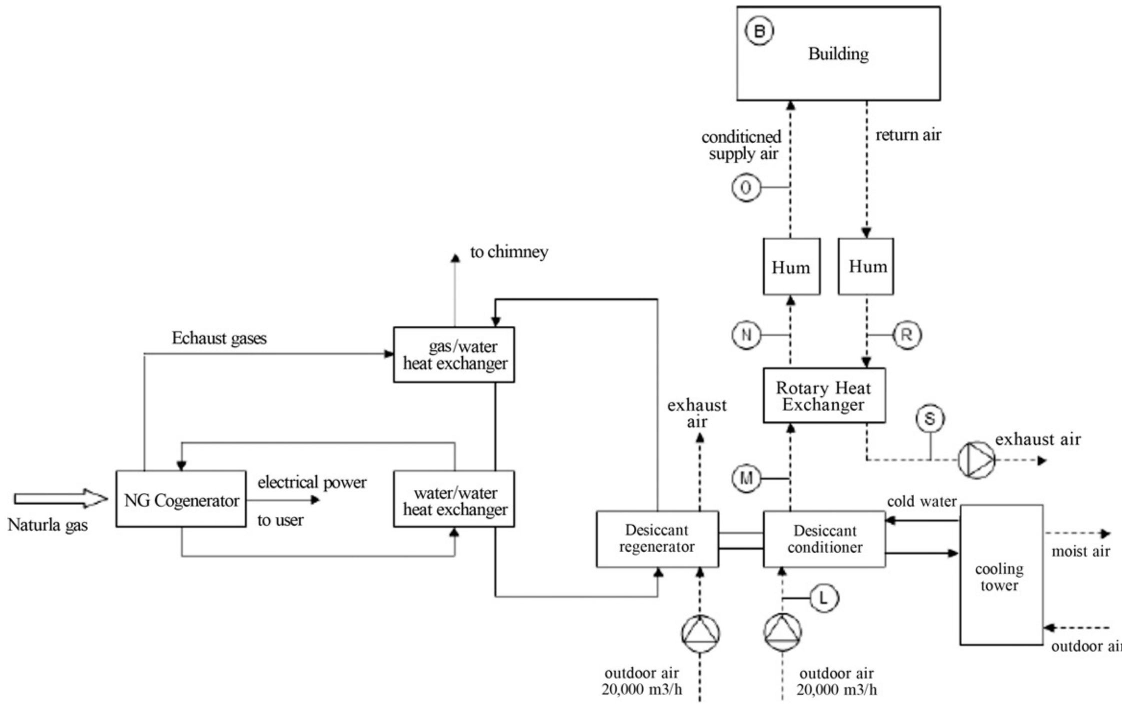

Fig. 19. Trigeneration plant with liquid desiccant [128].

solution side, solution concentration, and the air mass flow rates. In addition, it shows that the parallel configuration has no effect to the counter-flow configuration. Hence, parallel configuration is suggested with less pressure drop [134]. Sultan et al. [135] investigated the performance the packed tower regenerator. It shows that the regeneration process highly depends on the air inlet temperature, humidity and flow rate. Also, the regeneration rate decreases with an increase of the air humidity ratio and solution concentration. The evaporation of water from the desiccant increases with the increase of air and solution flow rate and temperature. In addition, Lowenstein [136] made investigation about the development of the liquid-based desiccant cooling system from the basic concept of the desiccant materials.

7.3. Application and evaluation

7.3.1. Temperate climate

Laevemann et al. [137] investigated the installation of the liquid desiccant cooling system in an office building. Well water temperature of 12–14 °C is used to cool the ceilings during summer. The lithium chloride water solutions desiccant dehumidified the outside air. The liquid desiccant is regenerated by the solar energy at 70–80 °C using solar energy with electric energy consumption for pumps and fans. Fig. 23 shows the schematic installation of the system in building. Chen et al. [138] investigated the actual installation of the liquid desiccant cooling system in real building. It shows it can reduce 30% of the cost compared to the conventional system (Fig. 24). In addition, it works very well even in very humid weather. Liu et al. [139] shows the application of the liquid desiccant cooling system in the demonstration building with cogeneration (Fig. 25). The results show the total efficiency of the cogeneration unit is over 80%. In addition, the thermal storage tank and the desiccant storage tank lengthen the operating hours resulting to the reduction of thermal energy from the gas-fired boiler, reduction of energy for compression chiller, and for the liquid desiccant system. In addition, in terms of the CO_2 emission, it is reduced to 60% more than that of the conventional HVAC system. Gasparella et al. [140] investigated the desiccant dehumidification with ground source heat

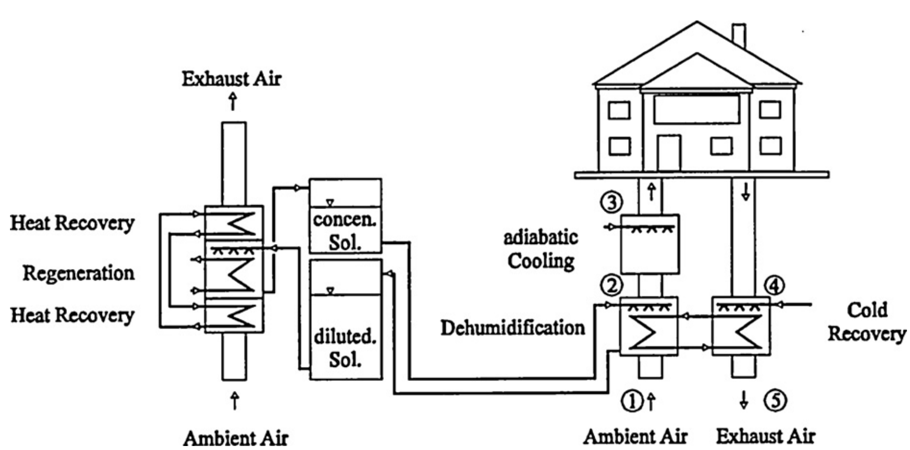

Fig. 20. Liquid desiccant with thermal storage [129].

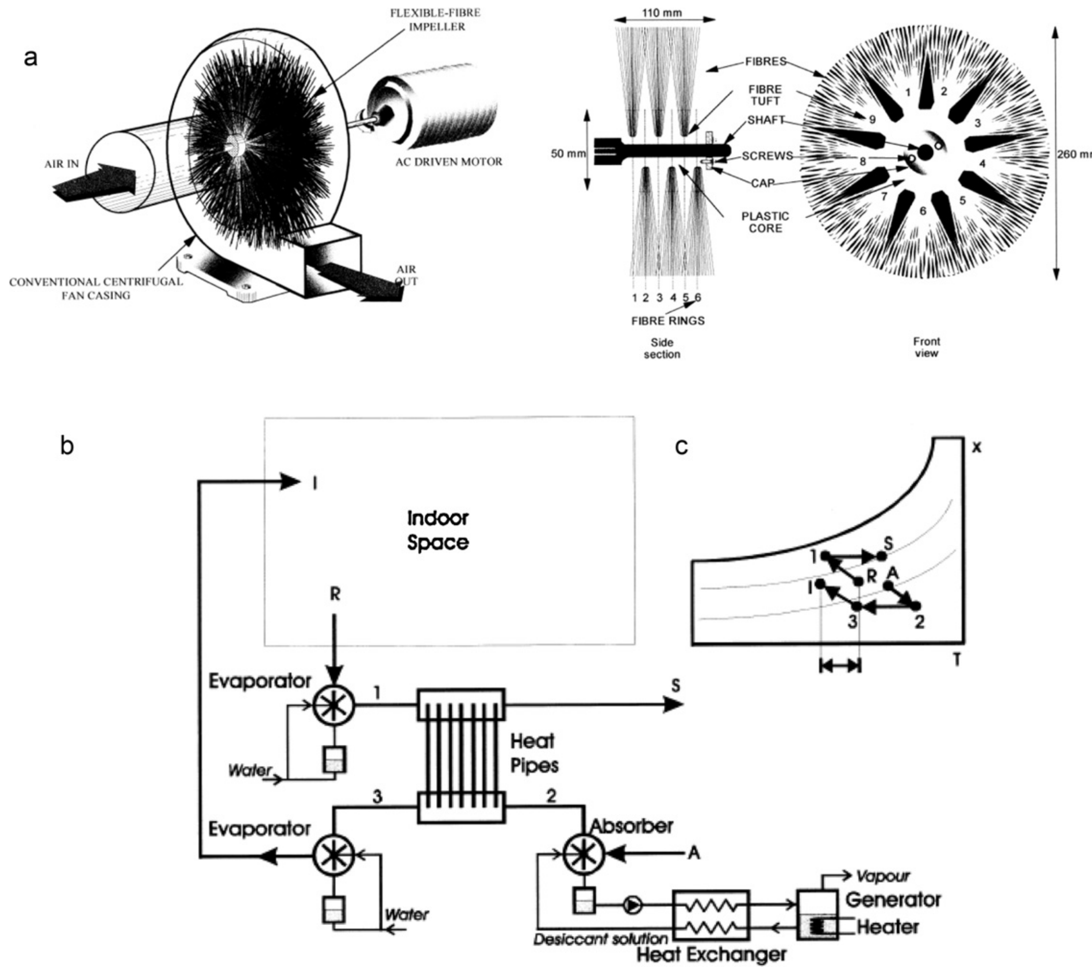

Fig. 21. Liquid desiccant cooling with rotating impeller absorber [131].

pump for modern office building in northern Italy. It used a liquid desiccant in packed column. The water from the borehole heat exchanger is used to control the air sensible load while the desiccant is used to control the air latent load. It shows that it saves 30% of primary energy compared to the conventional HVAC system. The concept of borehole heat exchanger had been conducted as potential for cooling of building in United Kingdom [141].

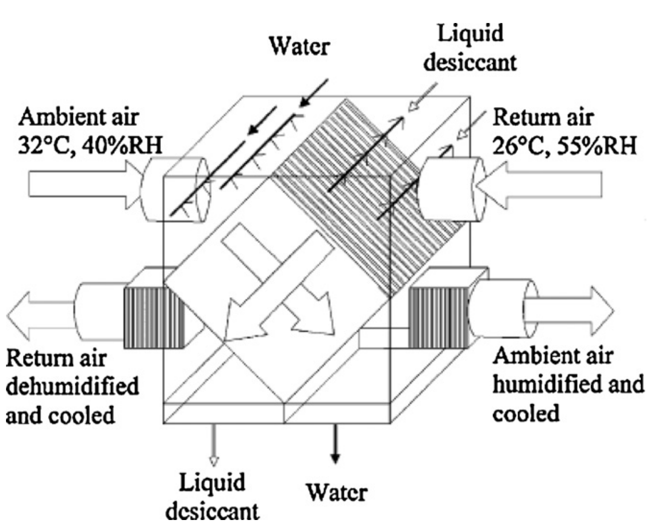

Fig. 22. Liquid desiccant heat exchanger absorber unit [132].

7.3.2. Sub-temperate and sub-tropical climates

Yong et al. [142] conducted experimental studies of the solid hybrid desiccant cooling system in Hong Kong, it shows that it is effective due to the part loading operation, thus applicable to humid climate. The part loading is based on three different operational modes: hybrid system in operation, only dehumidifier and IEC in operation, conventional vapor compression system.

7.3.3. Hot and humid climates (tropical, middle east and Mediterranean)

Katejanekarn et al. [143] presented the liquid desiccant cooling system powered by the solar energy installed in Asian Institute of Technology, Thailand (Fig. 26). The main advantage of this installation is the geographical location which is located in hot and humid tropical climate. It uses pure solar energy for the regeneration of the desiccant material and cool water for the cooling of air. Hence the system reduces the temperature by 1.2 °C and absolute humidity of 0.0042 kg/kg. One of the important limitations of the system is the cooling of air by using the cold water from the cooling tower. Since the outdoor air is humid, the water from the cooling tower cannot be reduced further. Jain et al. [144] investigated the liquid desiccant cooling system in hot and humid climate in 16 Indian cities. The results show the wet surface heat exchanger gives a consistently high COP but the air circulation rate needed per ton of refrigeration is also higher. The PRM (Process Recirculation Mode) and ERM (Exhaust Recirculation Mode) cycles fluctuate widely for different outdoor air conditions thus not suitable for tropical weather. The higher effectiveness values of the air

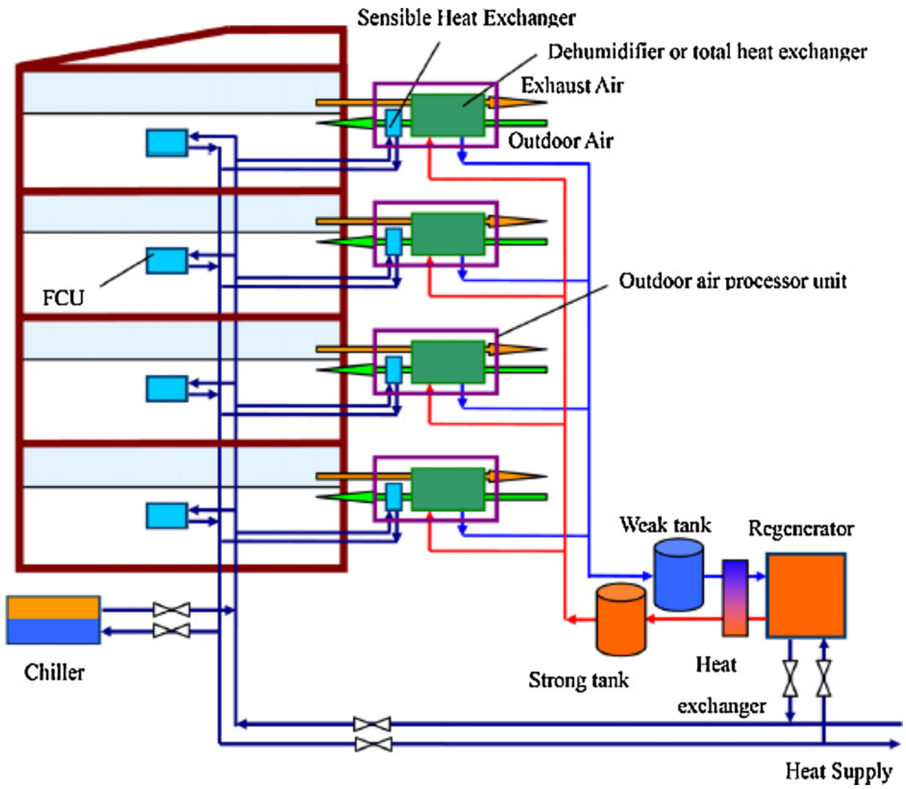

Fig. 23. Liquid desiccant cooling system applied in real building [138].

to air heat exchanger, lower cooling water inlet temperatures and dehumidification of air to lower humidity levels reduces air circulation rates and improves COP of cycles. An increase in the amount of ventilation reduces the cycle COP—should be keep in minimum

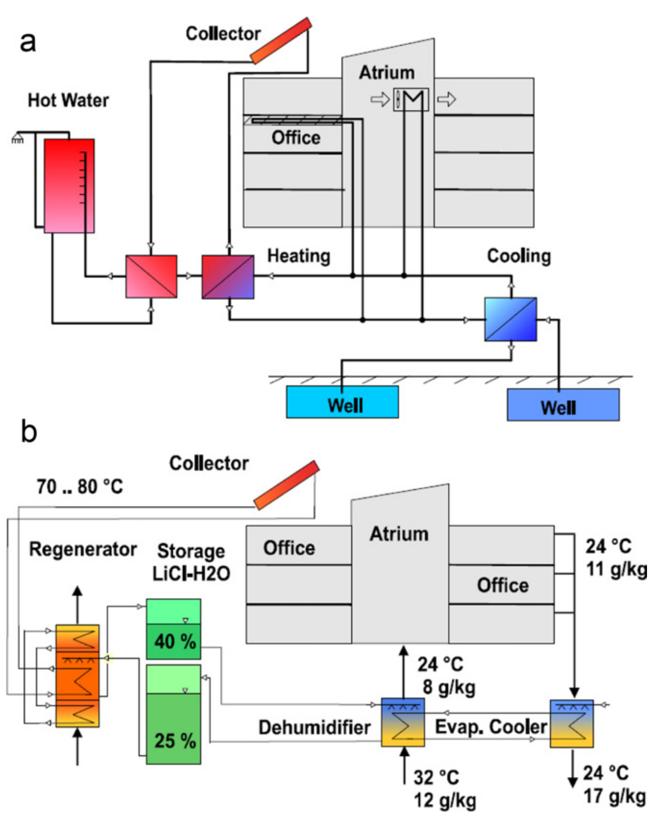

Fig. 24. Solar liquid desiccant cooling installation [137].

to maintain indoor air quality. Saman et al. [145] investigated the application of the liquid desiccant in the South East Asia climates. In three cities investigated—Bangkok, Jakarta and Singapore, it shows the potential of the system in combination with the vapor compression system, with the reduction of cooling energy and peak electric energy demand. Gahddar et al. [146] investigated the liquid desiccant cooling as a replacement to the vapor compression system. It shows that for the Beirut climate, the use of liquid desiccant reduces the latent load of the HVAC system. In addition, the performance is improved. Gommed and Grossman [147] investigated the solar powered liquid desiccant cooling system in Haifa, Israel. It is applied in the office buildings. In the parametric investigation conducted, it shows that factors of air condition (ambient temperature and flow rate) affected the heat and mass transfer in the dehumidifier. The temperature has little effect. The temperature and flow rates of heating and cooling water and the flow rate and solutions of desiccant in the dehumidifier and regenerator affects the humidity of the supply air. Kinsara et al. [148] investigated the application of the liquid desiccant cooling system in Middle East. The system uses calcium chloride as the desiccant. The liquid desiccant inlet temperature has effect to the performance of the system. The system coefficient of performance increases with the decrease of the space sensible heat ratio. The system performance is affected by the effectiveness of the heat exchangers. Zurigat et al. [149] investigated the air dehumidification with triethylene glycol desiccant in a packed column in the hot and humid climate. It shows that the moisture removal rate increases with increasing desiccant inlet concentration flow rate, and the air flow rate.

8. Hybrid desiccant cooling

The hybrid desiccant cooling system comprises of the desiccant cooling system and the heat pump. The main advantage of the hybrid desiccant cooling system is the increase of the heat pump performance compared to the pure heat pump system.

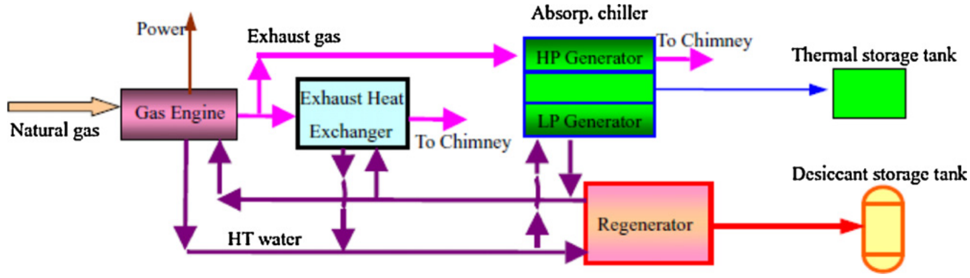

Fig. 25. Liquid desiccant cooling system with cogeneration [139].

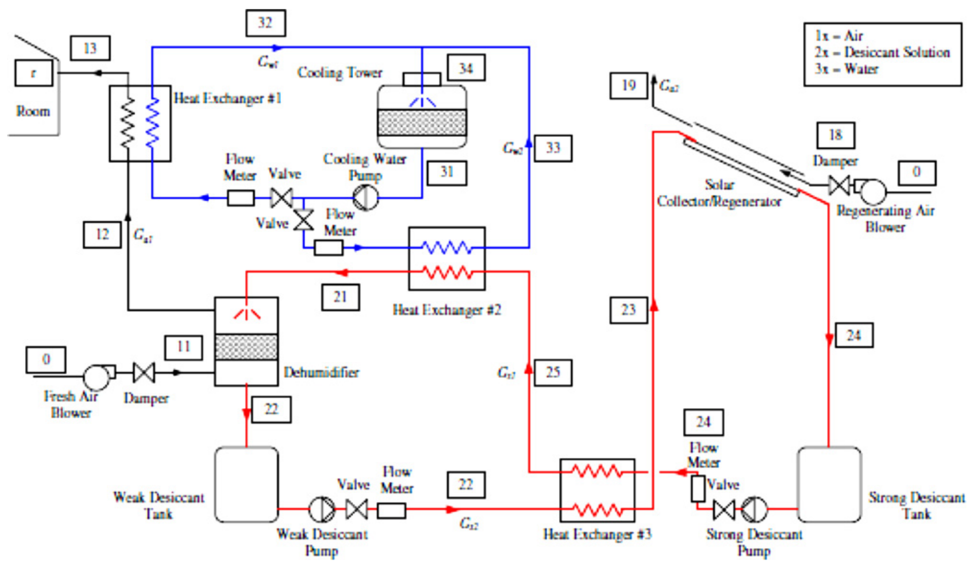

Fig. 26. Liquid desiccant cooling in Thailand [143].

8.1. Concept and operation

There are several designs of the hybrid desiccant cooling system. Liu et al. [150] presented the combined dedicated outdoor air system combined with the desiccant wheel (Fig. 27). It shows that energy saving is possible as long as there is source of solar energy and natural gas. The hybrid desiccant system is based on either solid or liquid desiccant materials used in removal of the air moisture content with the application of the vapor compression system as air cooler and desiccant regenerator. The main advantage of the hybrid system is the separate handling of air latent energy and of sensible energy contents. In this case, the vapor compression performance is increased since it handles only the air sensible energy content while the desiccant material handles the air latent energy content.

Hybrid desiccant cooling system is the realization of the separate handling of the air latent and sensible load by means of the desiccant material and vapor compression system. Hence, with the system, vapor compression energy consumption is reduced.

8.2. Development and evolution

There are many designs of the hybrid desiccant cooling systems. The design varies for large building applications to the small building application which is compact.

The typical solid based desiccant cooling system comprises of the rotating desiccant wheel and the vapor compression system which evaporator serves as the air cooler while the condenser serve as air heater with back-up thermal energy source. Dhar and Singh [151] studied several designs of the solid based hybrid desiccant

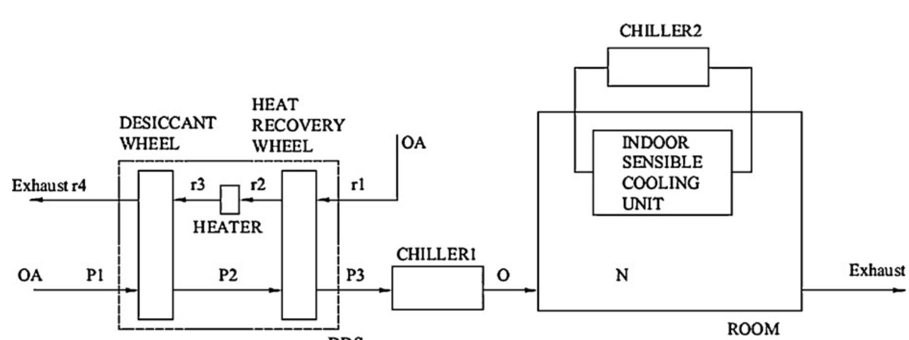

Fig. 27. Dedicated outdoor air system with rotary desiccant wheel [150].

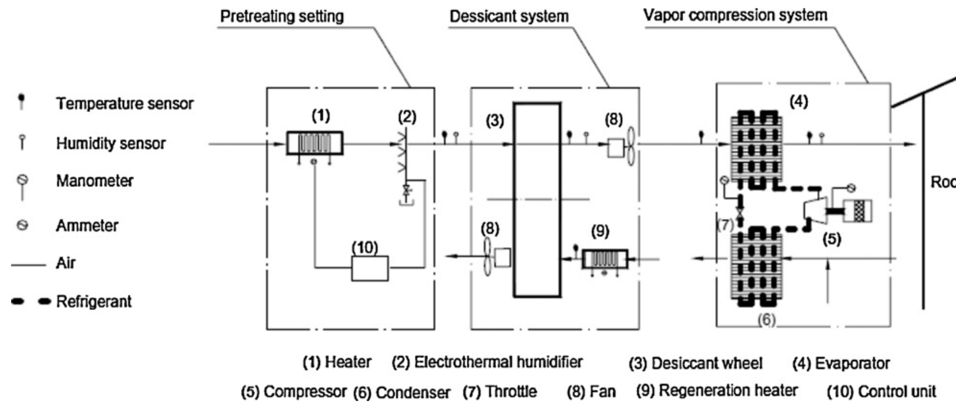

Fig. 28. Schematic diagram of the hybrid solid desiccant cooling system [152].

cooling systems. It shows that solid-based hybrid desiccant cooling system gives substantial energy saving as compared to the conventional vapor compressions refrigeration system. Jia et al. [152] show that it can reduce electric energy consumption by 37.5% compared to the ordinary vapor compression system at the same air condition of 30 °C and 55% humidity (Fig. 28).

Sheridan and Mitchell [153] investigated the application of the solid desiccant hybrid system applied in the Australian climatic condition. In the application with high sensible load air, the hybrid cycle save 24–40% electric energy compared to the conventional cycle. Combining the hybrid system with indirect evaporative cooler can give significant saving of the energy consumption. The hybrid system saves more energy in hot and dry climate than in hot and humid climate with more energy consumed than the conventional cycle. It can save energy when the air to be treated has high sensible load fraction than latent load fraction. Solar energy can be combined to meet the higher latent load of the air.

The typical liquid desiccant cooling system comprises of the falling film moisture absorber and desorber with vapor compression system evaporator as air cooler and condenser as air heater with back-up thermal energy source. Critical review of the development of the hybrid liquid desiccant cooling system is presented by Christodoulaki et al. [154]. The novel hybrid solid-based desiccant cooling system comprises of the desiccant-coated fin heat exchangers in the vapor compression system. The system operates in cyclic process. The novel hybrid liquid-based desiccant cooling system comprises of the falling film in the heat exchangers both for air dehumidification and humidification. Thus, the air dehumidification and cooling is done at the same time. Dai et al. [155] presented the experimental investigation of the liquid desiccant cooling system shown in Fig. 29. It shows the system cooling production is higher than the ordinary vapor compression system by 20-30%. The system coefficient of performance is higher than the ordinary system. Jeong et al. [156] investigated new designs of the solid hybrid desiccant cooling system—double desiccant wheel and four partitioned desiccant wheel shown in Figs. 30 and 31. The double wheels type makes the system regenerated at lower temperature as discussed by Ando et al. [77]. The four-partition desiccant wheel makes the system compact in the design. However, the main problem is the increase of the pressure losses due to changes of the air flow directions.

8.3. Application and evaluation

8.3.1. Temperate climate

Qin et al. [157] investigated the application of the solid hybrid desiccant cooling for the typical climate of Shanghai. The system combined the engine-driven chiller and the desiccant wheel shown schematically in Fig. 32. It shows the system can save more than 40% of the operational cost. Hence, waste-heat from the engine can be used both to support air cooling through chiller and for hot air for desiccant regeneration.

8.3.2. Sub-temperate and sub-tropical climates

Zhang [158] made comparison with different air dehumidification systems, the mechanical dehumidification with heat pump, mechanical dehumidification with sensible heat exchanger, mechanical dehumidification with membrane-based total heat exchanger, heat pump incorporating desiccant wheel and heat wheel in Hong Kong. The purpose of which is the reduction of the energy consumption with the increase of ventilation rate. It shows that the system can reduce energy consumption compared to the traditional vapor compression system. Ma et al. [159] shows the application of the desiccant cooling system in the hybrid air-conditioning in green building in Shanghai (Fig. 33). The result shows that the system is 44.5% better than the conventional vapor compression system at latent load of 30%. The performance is 73.4% better at latent load of 42%. If the liquid desiccant is powered by solar energy, the heat pump is eliminated with improvement of the electric coefficient of performance. However, the original cost will be higher and the operation depends on weather conditions. Aynur et al. [160] presented a field performance investigation of the heat pump desiccant unit. The system operates in cyclic process for air dehumidification and regeneration of a and b (Fig. 34). It shows the system can attain an air humidity ratio of 10 g/kg throughout the cooling system with better thermal comfort than of the heat recovery ventilation unit. In addition, variable refrigerant volume air conditioning system with heat pump desiccant has 26.3% less energy for operation. Mago and Goswami [161] investigated the hybrid liquid desiccant cooling system installed in the test house. It was found that the system improved the air conditioning performance by decreasing the outlet humidity and temperature. Also, it was found the system is cost effective when it is 100% fresh air ventilation than recirculation.

8.3.3. Hot and humid climates (tropical, middle east and Mediterranean)

Khalid Ahmed et al. [162] investigated the application of vapor-compression-liquid desiccant cooling system for hot and humid climate. It shows the COP is higher than 50% of the conventional vapor compression system. Beccali et al. [163] shows the installed hybrid desiccant cooling system in Palermo, Italy. It provides fresh air to the room of 450 m^3 (Fig. 35). The performance of the system with radiant ceiling is investigated. The regeneration is provided with solar collector and heat rejection from chiller. In case humidity ratio/temperature set-point of the supply air is not met, further

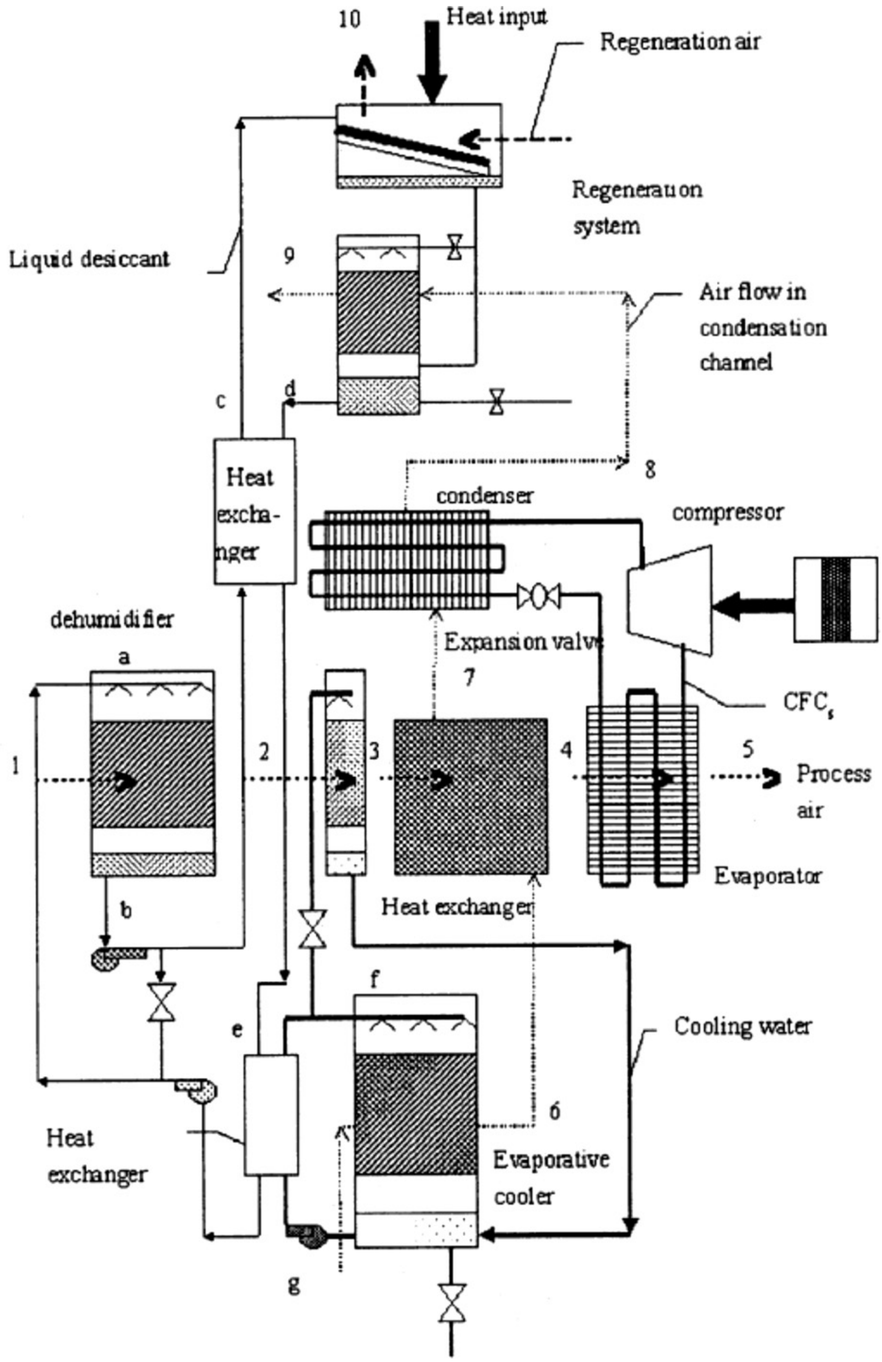

Fig. 29. Liquid desiccant hybrid system [155].

dehumidification and air cooling is by means of two auxiliary cooling coils. It shows it fairly works in summer with some further improvements of the system for increasing its performance.

9. Discussion and summary

The building sector is one of the major consumers of conventional energy sources in the form of electric energy [5,37,38]. The sector is also one of the largest contributors to the greenhouse gases. It is expected that the building sector energy consumption will continuously increase as urbanization, industrialization, and living standards are increasing every year. One of the major building sector energy consumption is for the maintenance of the indoor thermal comfort environment which is presently provided by the vapor compression air conditioning and ventilation system [27]. Passive and natural air-conditioning and ventilation system is an option in reducing building energy consumption without affecting the indoor thermal comfort condition. Fig. 36 presents the diagram of the natural and passive methods in indoor environment air-conditioning and ventilation. The application of wind-induced natural ventilation is based on prevailing wind speed and direction [164]. Many options about natural ventilations had been done [165]. In the case of the solar-induced ventilation, it is applicable for dry and cool air [166]. However, in the case of hot and humid air, direct application of outdoor air to the indoor environment causes a problem in thermal comfort. Hence, desiccant-based air dehumid-

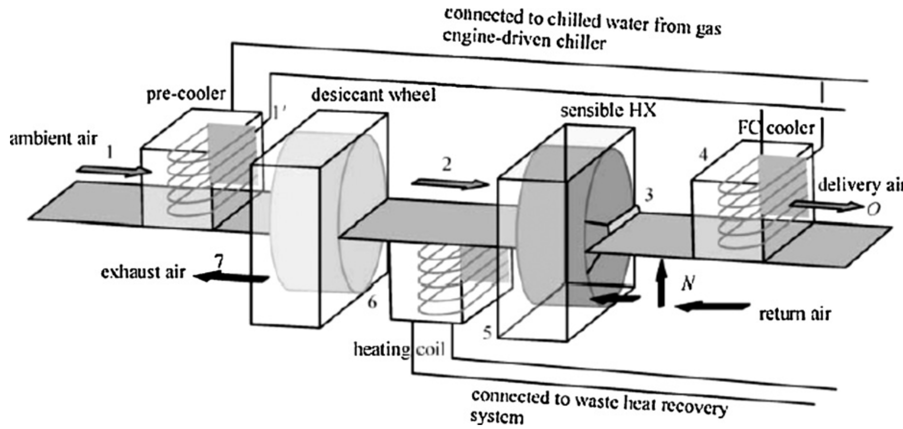

Fig. 30. Solid desiccant hybrid combined with engine-driven chiller [157].

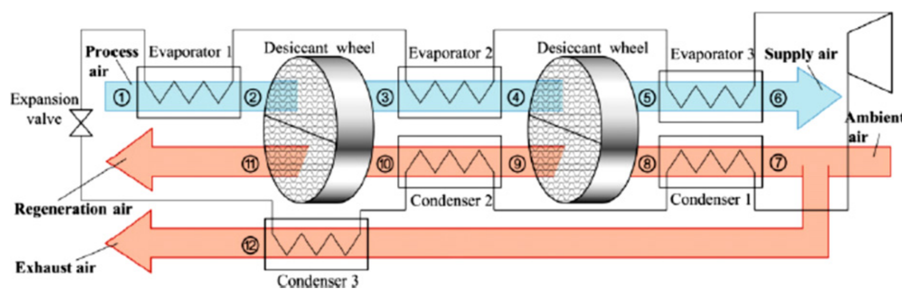

Fig. 31. Double desiccant wheels hybrid system [156].

ification and cooling is an option for reducing air moisture content and temperature with the application of alternative energy source such as solar energy.

The desiccant-based air-conditioning and ventilation system utilizes the capability of desiccant materials in removing the air moisture content by natural process—the sorption process. The sorption process (adsorption and absorption) is an interaction between the sorbent and sorbate molecules through intermolecular interaction. Since desiccant materials have low concentration of water vapor content, the air moisture content is attracted to the surface of the desiccant materials due to the moisture vapor pressure difference between the air and the desiccant surface. In order for the desiccant material to be used again, application of thermal energy is necessary to remove the moisture in the desiccant materials. Fig. 37 shows the operational concept and diagram of the desiccant-based ventilation and air-conditioning system.

The processed air from the desiccant dehumidifier becomes hot due to the release of the heat of condensation and heat of sorption. Heat recovery devices are used to recover this energy for application again in the desiccant dehumidifier in conjunction with other sources of thermal energy. The condition of the air after the heat recovery becomes warm and dry. As in many applications, the air condition is still above the thermal comfort temperature, so that evaporative cooling process is applied by either direct addition of air moisture or indirect addition of air moisture in secondary air stream. The application of evaporative cooling process reduces the air temperature with either slight increase of air moisture content or constant air moisture content.

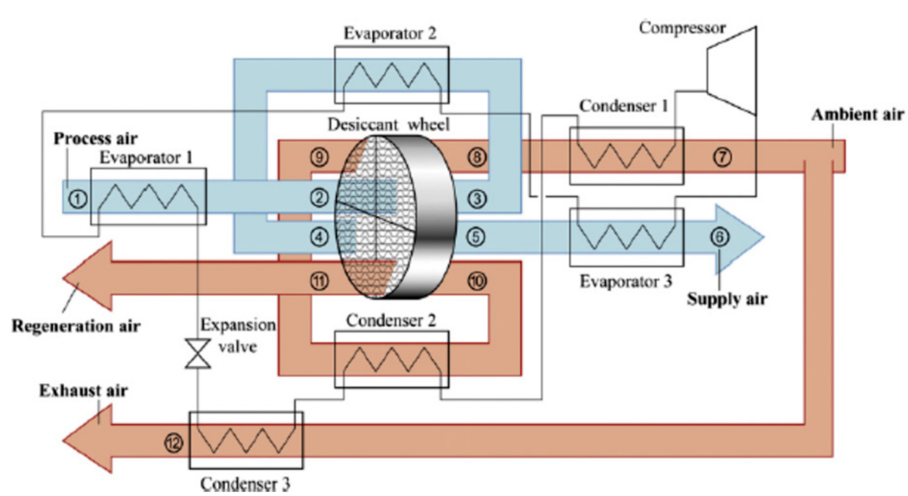

Fig. 32. Four-partition desiccant wheel hybrid system [156].

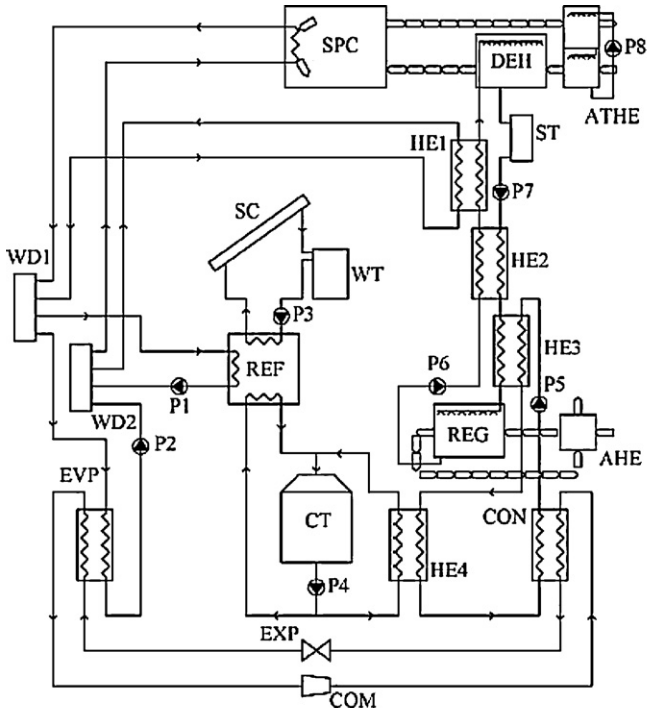

Fig. 33. Hybrid air-conditioning system in green building [159].

In addition, application of other air cooling techniques both conventional and non-conventional can also be used as an additional air cooler prior to the introduction of the air to the indoor environment. The conventional air coolers such as absorption chillers and vapor compression system are used with an increase of its performance. The non-conventional coolers such as ground source heat pump and water source heat pump can also be used. These auxiliary coolers are applied when the needed temperature of the air after the evaporative cooler is still not enough for the maintenance of the indoor thermal comfort condition.

9.1. Benefits of the desiccant cooling

Desiccant materials are used for air-conditioning applications with advantages when [68]:

(1) The latent load is large in comparison to the sensible load.
(2) The cost of energy to regenerate the desiccant is low when compared with the cost of energy to dehumidify the air by chilling it below its dew point.
(3) The moisture control level required in the space would require chilling the air to subfreezing dew points if compression refrigeration alone were used to dehumidify the air.
(4) The temperature control level required by the space or process requires continuous delivery of air at subfreezing temperatures.

Thus, running of desiccant cooling system will be cheaper than the vapor-compression cooling system and initial capital cost is lower when the above conditions are met. In addition, the desiccant materials such as titanium dioxide (TiO_2) absorb other types of pollutants present in the air such as bacteria and viruses through photocatalytic process [167]. With this, the desiccant cooling system makes the air quality high without additional cost for the installation of air purifiers in the vapor-compression system.

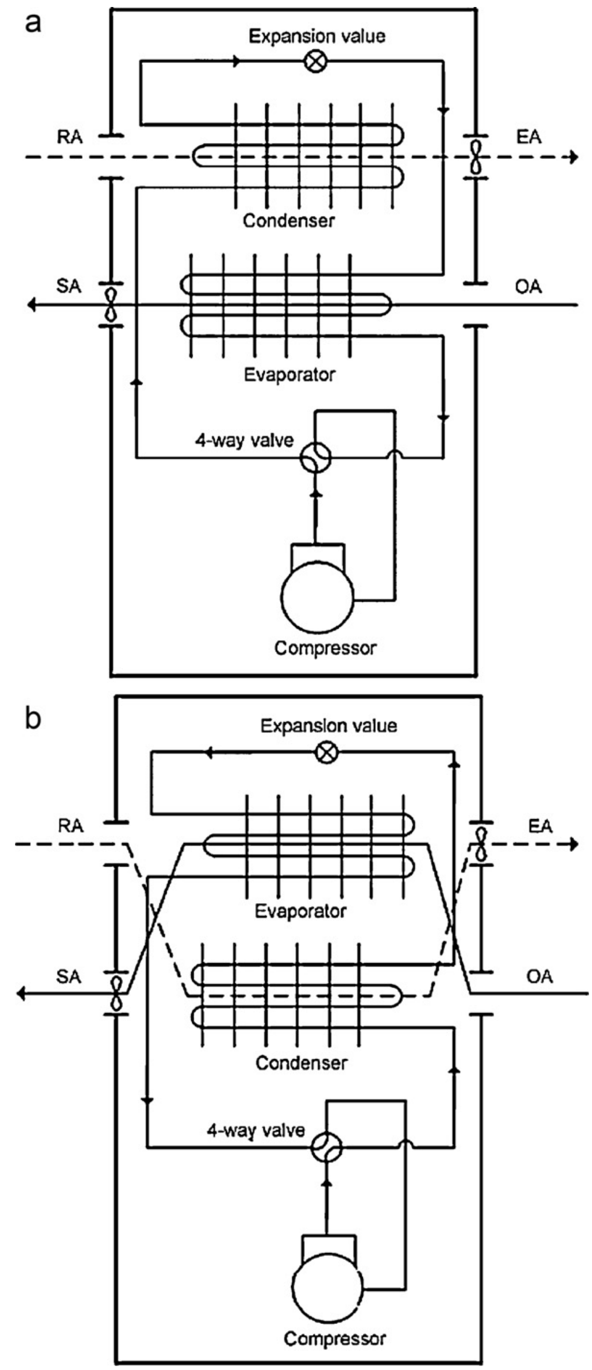

Fig. 34. Heat pump desiccant unit [160].

Most of the energy consumption for the operation of the desiccant cooling system is for the reactivation of the utilized desiccant materials. For the temperature operation of the desiccant cooling system, the regeneration energy is for [68]:

(1) The heat required to increase the desiccant surface temperature high enough to make the vapor pressure higher than the surrounding air.
(2) The heat needed to vaporize the moisture on the desiccant surface.
(3) The heat of desorption for water from the surface of the desiccant.

Table 1
Global development and application of the thermally activated desiccant cooling technologies.

Continent	Country	Solid desiccant system	Liquid desiccant system	Hybrid desiccant system
Africa	Egypt	0		
	Kenya	0		
Asia	China	0	0	O
	India	0	0	O
	Iran	0		
	Iraq	0		
	Israel	0	0	0
	Japan	0	0	0
	Kuwait		0	
	Lebanon	0		
	Pakistan	0		
	Quatar		0	
	Saudi Arabia	0	0	
	Singapore	0		
	South Korea	0		
	Thailand	0	0	
	Turkey	0		
Europe	France	0		
	Germany	0	0	0
	Italy	0	0	0
	Poland	0		
	Sweden	0	0	
	Switzerland		0	
	United Kingdom	0		
North America	Canada	0	0	
	Mexico	0		
	USA	0	0	0
Oceania	Australia	0	0	0
	New Zealand		0	
South America	Cuba	0		
	Brazil	0		

Other countries may have research, development and application.

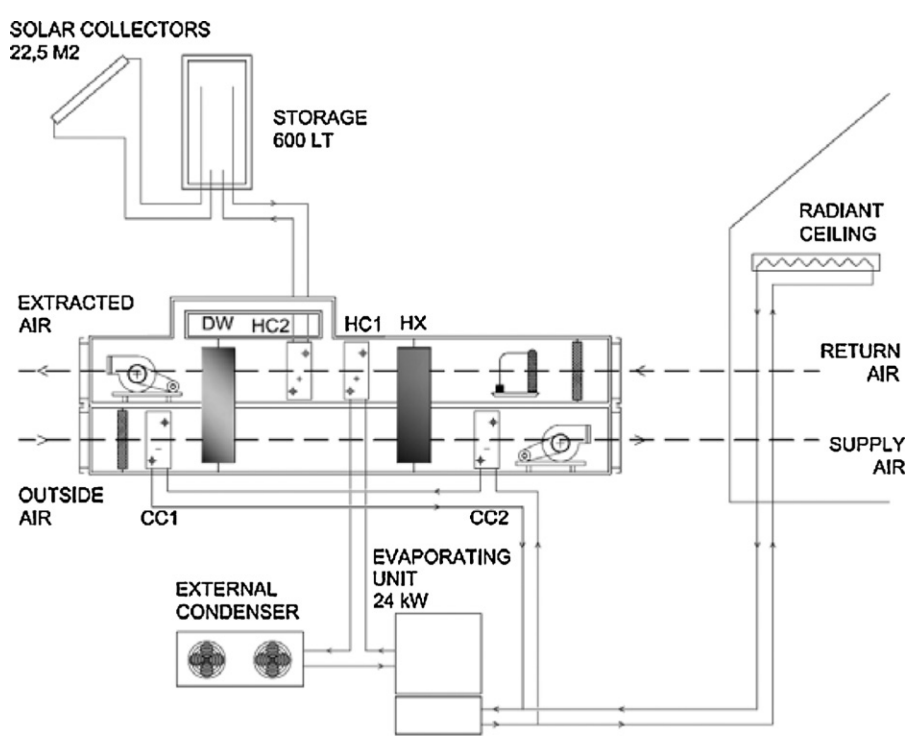

Fig. 35. Hybrid desiccant cooling system [163].

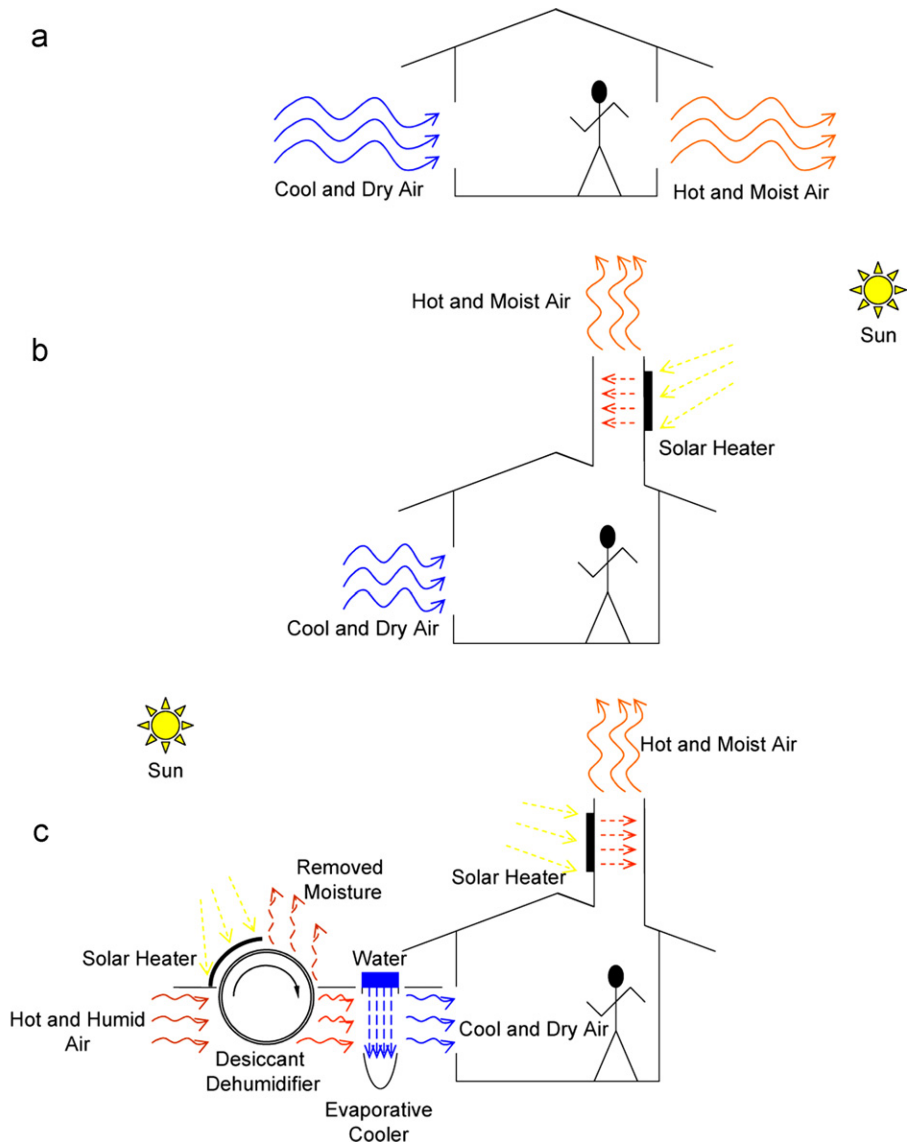

Fig. 36. Natural and passive air-conditioning and ventilation systems: (a) wind-induced, (b) solar-induced and (c) solar-desiccant.

Some of the energy consumed in the operation of the desiccant cooling system is for the air fans; moving the air both for the dehumidification of outside air and of the reactivation/regeneration of the desiccant material. The other energy is for the operation of cooling process of the air prior to introducing it to the indoor environment. Hence, application of the solar thermal/photovoltaic system can complement the system electric energy consumption [63,64].

Several studies had been conducted on the desiccant cooling system since the invention of honeycomb wheel by Carl Munter from Sweden. Several review papers mentioned on this such as of Yu et al. [50], Grossman and Johannsen [51], Kim and Infante Ferreira [52], Afonso [53], Grossman [56], Mazzei et al. [66], Waugaman et al. [168], Daou et al. [169], Wang et al. [170], Desideri et al. [171] and Balaras et al. [172]. And review conference paper such as of Saman et al. [173]. Feasibilities studies were conducted about the application of desiccant based cooling system using renewable energy such as solar as main energy source; the studies of Halliday et al. [105] shows that desiccant based system is applicable in temperate climate such as of United Kingdom. In addition, the studies of Mavroudaki et al. [101] shows that the desiccant based cooling system is not applicable when the relative humidity is high such as of Mediterranean areas due to higher regeneration temperature requirement [59,153]. Henning et al. [59] studied the design of desiccant cooling system for humid climates such as of Mediterranean areas in which it is applicable.

Several variations of desiccant cooling system are being conducted such as how it will be applied in hot and humid climate economically. The studies conducted by Ando et al. [77] shows the double dehumidification process in which two desiccant wheels being utilized can be used with low regeneration temperature. The purpose is to increase the dehumidification rate using low temperature thermal energy sources. Enteria et al. [94] and Enteria et al. [95] shows the different design of the desiccant-based cooling system in which the cooling of the dehumidified air is done through constant humidity process (desiccant dehumidification and indirect evaporative cooling). The processes avoid the deep dehumidification process in the case of the typical system such as employing direct evaporative cooler in the supply air.

Desiccant based-cooling system controlled the indoor air-quality as reported by Zhang et al. [174]. Based on the studies conducted by Fang et al. [175], desiccant coated wheel removed VOCs of air, and most particular the most common VOCs, the toluene and n-hexane [176]. Thereof, the desiccant-based cooling

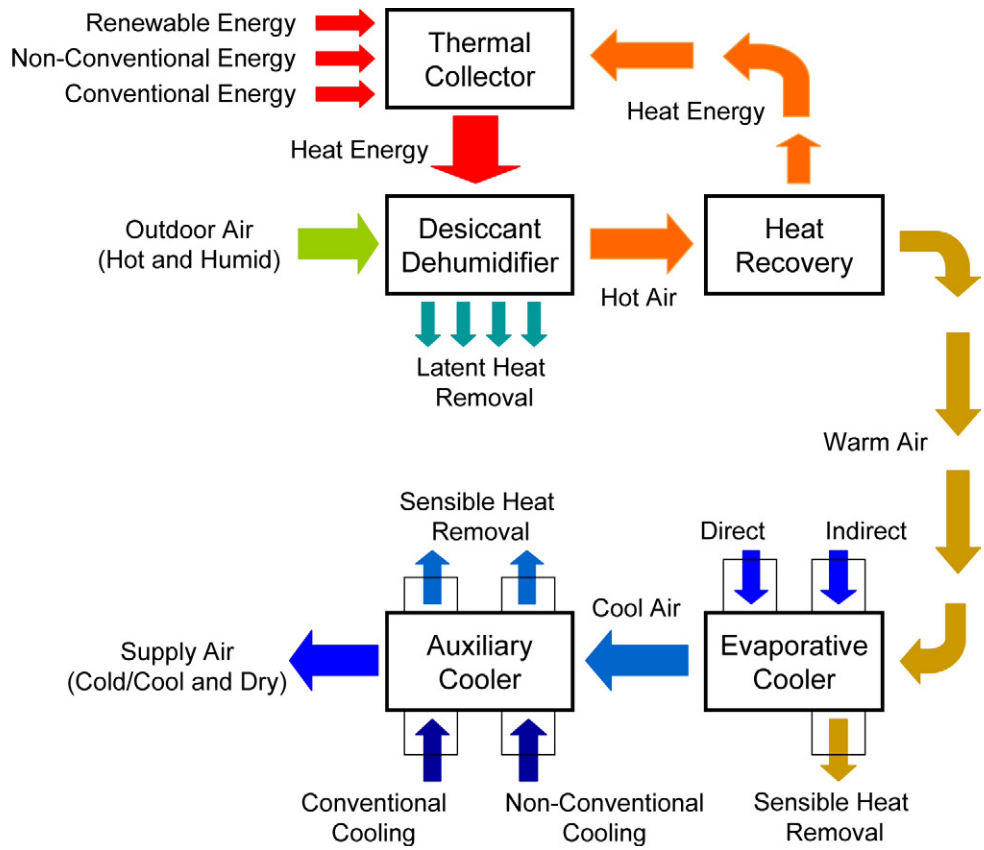

Fig. 37. General concept of the thermally activated desiccant cooling technologies.

system not only solved the health problem related to the moisture of the building [177], but, also the problem of indoor air quality. With this, it can also be added for the management of the indoor environment such as for office buildings which is reported by Shaw et al. [178] of the National Research Council of Canada. Most important, the desiccant-based cooling system can be applied to solve the issue of energy, comfort, environment, and indoor air most particularly for sensitive occupants such as nursing care [179]. Nevertheless, it was shown by Goswami et al. [167] that the titanium dioxide (TiO_2) desiccant material can be used to control air microorganisms through photocatalytic process.

9.2. Classification of desiccant cooling

The main classifications of the desiccant-based system is based on the desiccant materials used in the reduction of the air moisture content and the application of the desiccant material with common air handling systems. Fig. 38 shows the classifications of the desiccant-based air dehumidification and cooling systems.

The solid desiccant-based system uses solid desiccant materials in the removal of air moisture content. There are several kinds of solid desiccant materials—silica-gel, titanium silicates, calcium chloride, activated aluminas, zeolite (natural and synthetic), molecular sieve, lithium chloride, organic-based desiccants, polymers and composite desiccants. The application of these materials depends on the cost, operating conditions, and the source of thermal energy [51].

The liquid desiccant-based system utilizes liquid desiccant materials in removing air moisture content. The widely used liquid desiccant materials are the lithium chloride, lithium bromide, calcium chloride and glycol-based substance. Also, the application of these materials depends on the cost, operations, and the source of thermal energy. In addition, as some of liquid desiccants are corrosive, and require proper handling in their application [51]. However, the main advantage of the liquid desiccant is its high moisture removal capacity with lower regeneration temperature requirement.

The hybrid-based system is based on either solid or liquid desiccant materials used in removal of the air moisture content with the application of the vapor compression system as air cooler and desiccant regenerator. The solid-hybrid desiccant cooling system is usually a combination of the vapor compression system and of the rotating desiccant wheel [153]. The condenser of vapor compression system serves as the regenerator of the desiccant wheel, while, the evaporator serves as the air cooler of the processed air (after desiccant wheel) [152,153]. The main advantage of the hybrid system is the separate handling of air latent energy and of sensible energy contents. In this case, the vapor compression performance is increased since it handles only the air sensible energy content while the desiccant material handles the air latent energy content.

9.3. Development and application of the desiccant cooling

The thermally activated desiccant cooling technologies are a promising alternative to the vapor compression system in handling air sensible and latent energy contents. This is due to the operation of the system which can be made possible by other energy sources—solar energy, waste heat and others.

The research on the solar-desiccant ventilation and air-conditioning system is very important due to the fact that the amount of air thermal energy content is almost in phase with the amount of solar radiation [55]. In hot and humid climate, such as in East Asia during summer time and South East Asia for whole year round, the air temperature and humidity are high. In addi-

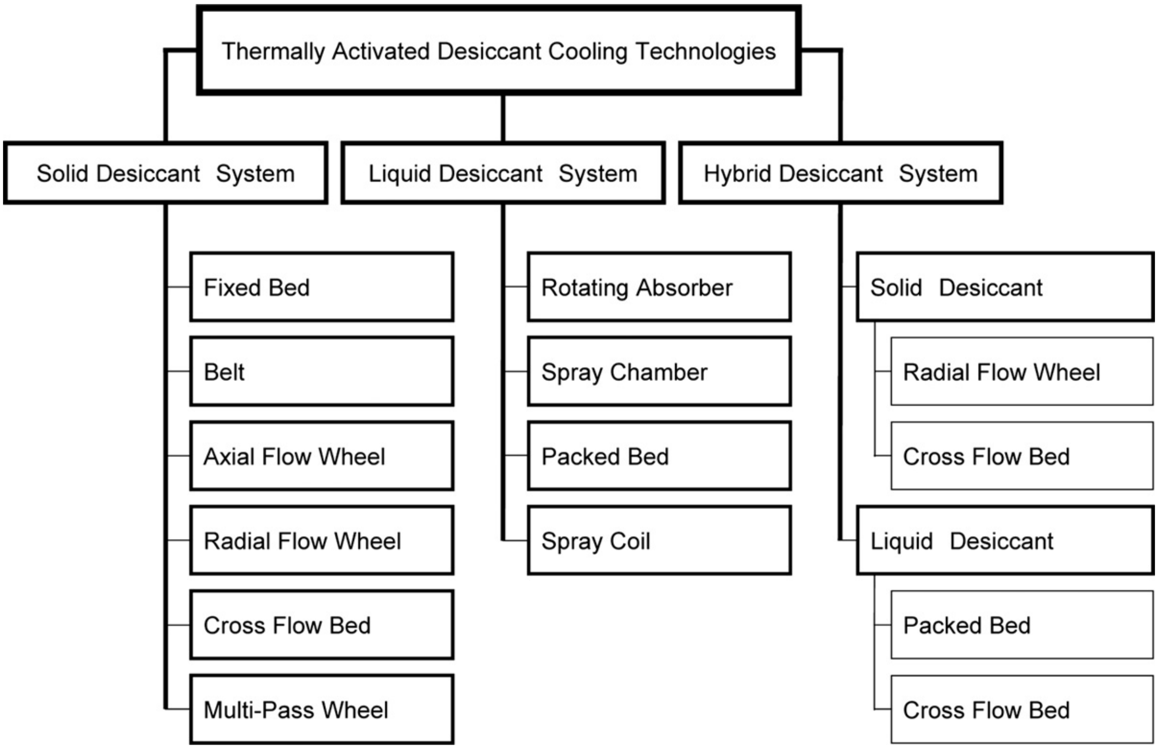

Fig. 38. Classifications of the thermally activated desiccant cooling technologies.

tion, as daylong dehumidification is needed compared to the other climatic conditions, the cheaper and available nighttime electric energy (off-peak) can be stored for daytime operation of the system [180]. Enteria et al. [94] shows the applicability of nighttime electric energy storage for daytime utilization. Combined solar energy for air dehumidification with ground water source for air cooling makes the system utilize natural energy sources such as done in London [181].

The vapor compression system operates to remove the air moisture content by cooling the air below its dew point temperature. However, as the air after cooling to its dew point temperate is very cold, reheating of the air is needed before it will be introduced to the indoor environment. As the Asia-Pacific region is very hot and humid all-year-round in the South East Asia and during summer time in East Asia, the vapor compression system operates thoroughly to reduce the outdoor air very high moisture content. Application of the desiccant material coupled with the vapor compression system minimizes the operating condition of the vapor compression system since the desiccant material handles the air latent energy content while the vapor compression system handles the air sensible load (hybrid desiccant). In application conducted of the liquid system, it can have a higher performance of 44.5% applied in green building [159]. The advantage of the hybrid desiccant cooling system is its operation in part loading [152].

Table 1 shows the development and application of the desiccant-based air dehumidification and cooling system. The development and application of the desiccant-based ventilation and air-conditioning system is expanding globally. However, in the hot and humid climate of the Asia-Pacific Region, South America and Africa, the system is still not fully utilized. Thereof, investigations of the system for applications in these regions expand the potential of the system for wider application. Hence, the system is a potential as one of the ventilation and air-conditioning technologies for hot and humid climates energy-efficient healthy buildings [182]. The greater effect of which is the reduction of conventional energy consumption and greenhouse gases emissions contributed by the building sector in providing human thermal comfort condition.

Acknowledgement

This research is supported by the Global Center of Excellence (GCOE) Program of the Tokyo Polytechnic University.

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